DESIGN OF A CRIB MOBILE TO SUPPORT STUDIES IN THE EARLY DETECTION OF CEREBRAL PALSY

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DESIGN OF A CRIB MOBILE TO SUPPORT STUDIES IN THE EARLY DETECTION OF CEREBRAL PALSY

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To my parents who always encouraged me to want the best for myself

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SUMMARY

The aim of this research is to explore innovative methods to support the early detection of neuromuscular disorders like cerebral palsy in preverbal infants, which is crucial for early intervention treatments of at risk infants. This research focuses on the use of a goal and reward based mechanism to elicit kicking movements from infants between the ages of 2 to 4 months old. The intention is to encourage kicking in preverbal infants by enriching their natural environments through the modification of toys that infants are already accustomed to. In this way, different stimuli can be introduced into the infant's environment and their effect on infant behavior and motion can be studied without introducing unfamiliar objects to the infant environment.

This research consists of a two stage effort. The first part of the research is concerned with the design of a modified crib mobile to introduce different stimuli into the infant's environment. This stage is primarily concerned with the physical, electrical and software design of the crib mobile and the control device. The design of the crib mobile also requires a detailed investigation into selection of stimuli able to optimally evoke infant kicking movements. In our research, we utilize, music, motion and lights (henceforth referred as audio, movement and visual stimuli respectively) - all three stimulus are normally found in infant toys, to encourage kicking by infants.

The second part of this research investigates the effects of these stimuli on infant kicking. We introduce these stimuli individually i.e. each infant is only exposed to one stimulus. We then use videos recorded of infant activity in the presence of the stimulus and in absence (control) to determine if there is a significant increase in infant activity measured

on three metrics of infant kicking kinematics namely the frequency of kicking activity, the frequency of bilateral vs. unilateral kicking and the maximum and average duration of continuous kicking by the infant in the test groups exposed to the different stimuli.

INTRODUCTION

Early intervention for infants with development disorders such as Autism Spectrum Disorder and neuromuscular diseases like cerebral palsy has become an important area of research. Most studies that conduct assessments for at-risk infants are based on randomized control trials which means that, most of the time, the results noted by these studies are undermined because of the imprecise selection of participants projected as at-risk. As noted by [1] and [2] early identification markers that are used to identify at-risk infants are often not well established. This has sparked alternate research in the field of early identification of these disorders in infants, some of which we discuss in Chapter 2.

Preverbal infants interpret actions differently from adults. Research by Csibra [3], provides evidence that preverbal infants understand actions as either goal-driven or as associated with an object or an agent. For example, pointing at a car highlights an inference about the car and is therefore about the agent. On the other hand, observing an attempt to open a bottle highlights the goal, which is to pour or drink the contents of the bottle [3]. This means any form of behavioral encouragement for preverbal infants would need to be either defined as a goal or as a reference about an object. When infants identify an action as a goal they are able to infer the purpose behind that action even if they have not observed a successful attempt at achieving the specific goal at first or as part of training. Once they identify the goal, they can imitate the action to achieve that goal and even come up with new methods of achieving the goal if they are unsuccessful at first. Their research also suggests that infants tend to show a preference for efficient means of achieving a goal. If the goal changes then the same action, that was used to accomplish a previous goal, is deemed unnecessary by infants. This means any form of behavioral encouragement that encourages movements would need to be modeled based on achievement of a goal or as a reference associated with an object. Meltzoff’s study (1995) [4-5] supported this behavioral characteristic among 18 months old infants. Meltzoff’s research suggested that it is possible to communicate a desired behavior to an infant through short term goal assignment.

This goal-oriented approach was used by Morgan et al. [1] to test the efficacy of GAME (Goals -Activity -Motor -Enrichment) which focused on providing early intervention for preverbal infants at risk of cerebral palsy within the first year of their life. The intervention was based on short term goals identified by parents of at-risk infants, such as weightbearing to improve muscle strength and “sit to stand” motion from the parent’s lap to encourage standing. The neuromuscular development of these infants was then tested against a standard care group on metrics of Goal Attainment Scaling (GAS) and Peabody Developmental Motor Scales-second edition (PDMS-2). The standard care group had received therapy intervention that was aimed at motion learning and developmental skill through physical guidance for movement and training parents on different handling and positioning techniques. The study showed slight but not significant results between the test group introduced to GAME and the Standard Care (control) group on the Goal Attainment Scaling. However, there was significant improvement in motor function on the PDMS-2 scale of the test group as compared with the control group. This empirically proves that goal-oriented assignments can be used to improve certain behaviors in infants.

Based on this preliminary evidence, our research builds on this understanding of infant interpretation of actions as goals and behavior modification in infants through goal oriented tasks, with the aim of eliciting kicking behaviors from infants. This is accomplished through the design of a crib mobile, which is based on using kicking as the action to achieve the desired goal of activating one of the three stimuli incorporated in the crib mobile. Given that these three types of stimulus are widely present in infant toys and serve as a source of enjoyment for infants, our hypothesis is that the achievement of the stimuli activation goal through kicking is likely to also serve as a positive reinforcement or a reward for the infant to encourage kicking behavior. This class of experimental setup where goal achievement is rewarded is also found in studies conducted with infants at risk of Autism Spectrum Disorder (ASD) to encourage communication and social behavior among infants [2]. This further validates that any intervention that is aimed at behavioral modification for children should also be based on infant psychology and natural behavioral modifications. Details on the crib mobile design consideration are discussed in Chapter 3. Chapter 4 discusses the electrical, physical and software design of the crib mobile in light of the above findings. Chapter 5 talks about the experimental protocol used in data collection. Chapter 6 then discusses the metrics that are used to study infant kinematic movements, Chapter 7 discusses the results and analysis of our pilot study, Chapter 8 is a discussion on this research effort and Chapter 9 states the limitation of this research and projects future work.

CHAPTER 1. LITERATURE REVIEW

Cerebral palsy is a neuromuscular development disorder that is caused by a non-progressive impairment to the fetal brain and results in permanent motor impairment which affects movement and posture development [6][7]. Cerebral palsy effects roughly 3 to 4 out of every 1000 infants born in the U.S.A and the risk is likely to increase to 8 to 40% of high risk populations such as preterm infants [8][7]. Given its high prevalence in at-risk populations, there is an increased emphasis on providing early interventions to infants in the first few years of their lives when there are essential brain development milestones to achieve [1]. In this chapter, we discuss early detection methods that exist to facilitate these early intervention efforts and also highlight how our research contributes to developing a more feasible early detection mechanism. We also discuss studies that capitalize on the design of a crib mobile to test learning and memory among infants which will serve as the basis for our experimental design.

2.1 Conventional Early Detection Methodologies

Early detection of neuromuscular development in infants has led to the use of several clinical methods for determining cerebral palsy in infants. According to a comparative review conducted by Bosanquet et.al [7] which reviewed predictive tools for cerebral palsy in infants, the Prechtl General Movements Assessment (GMA) Test was found to be the most reliable tool for predicting Cerebral Palsy in infants when compared with MRI, Cranial Ultrasound and Neurological Examinations. The GMA tool relies on observing the natural movements of infants in the early ages of their life and then classifying them as belonging to the five categories of movements observed in infants. Typically developing infants exhibit either General Movements or Fidgety Movements and they are characteristic of healthy motor development among infants. General Movements involve the whole body and vary in intensity and force; they eventually develop into ellipsoid movements termed as writhing movements of small to moderate amplitude and speed at term age [26]. Fidgety Movements are characterized by movements of the entire body in all directions among infants of 9-20 weeks post-term age [26]. General Movements that are characteristic of abnormal development among infant include Poor Repertoire, Cramped Synchronous, Chaotic, Absent Fidgety and Abnormal Fidgety Movements. Poor Repertoire Movements are marked by a lack of complexity. Cramped Synchronous Movements occur when there is a simultaneous contraction of the limb and trunk muscles affecting fluency of movement. Chaotic Movements refer to movements with large amplitudes of motion. Fidgety and Abnormal Fidgety Movements are characteristic of either absence of the normal fidgety movements or the jerkiness in fidgety movements [26].

Results of Bosanquet et al [7] review were based on five metrics. Based on the data provided by the different studies, they calculated 1) specificity which they defined as correct negative diagnosis for CP, 2) sensitivity which was defined as correct positive diagnosis for CP, 3) positive likelihood ratios, 4) negative likelihood ratios which was defined as the likelihood that a positive or negative diagnostic respectively, for CP will change and 5) diagnostic odds ratio. As per their assessment, GMA was identified to have the highest sensitivity and specificity as compared with the other three diagnostic tools under review. This was due to observing and identifying characteristic movements in infants such as cramped movements and fidgety movements instead of the collective set of abnormal movements in infants. The GMA test also gained preference because of its feasibility with being able to retrospectively carry out diagnosis of CP through recorded video assessments which made it time and cost efficient. However, there are limitations associated with using GMA as a test for CP. The first limitation, which it shares with other clinical methods discussed in the review, is the expertise and standardization training required to code the observations. Furthermore, studies that used the various diagnostic tools were mostly conducted on pre-term infants whereas term born infants constitute 68% of the CP population. Furthermore, GMA only provides a qualitative assessment of CP diagnosis and cannot determine severity [1][9]. GMA can also be only used up to 4 months of age [9].

Magnetic Resonance Imaging (MRI) is another clinical assessment used for CP diagnosis in infants. Studies that relied on MRI as a diagnostic tool had sensitivity and specificity of 86% and 87 % respectively and were effective in diagnosing CP in term born infants [7]. However, one major limitation of MRI is that it requires infants to stay stationary for up to 30 minutes which can prove to be discomforting for the infant and hence clinically infeasible. Cranial Ultrasound had a sensitivity and specificity of 70-96% and 69-99% respectively, but for higher accuracy required that periodic scans were carried out on preterm infants until they reached term age [7].

Neurological Examinations such as the Lacey Assessment of Preterm Infants and Hammersmith Infant Neurological Examination had a sensitivity and specificity of 57-86% and 45-83% respectively [7]. They were however, found to be more sensitive than GMA in cases when GMA was ineffective. The limitation of these examinations stem from two factors. The first is that they are contingent on examiner experience as well as child restlessness. Both these factors tend to be difficult to standardize in examinations. Secondly, they are susceptible to misattribute behaviors in preterm infants such as dystonia and jitteriness to CP [7].

Other assessments such as the Bayley Infant Neurodevelopment Screener are also used to assess infant development however, as discussed above, there are limitations to the application of these techniques in CP diagnosis as they either provide a solely qualitative analysis, require the assessment to be done in a medical or clinical facility, or are heavily reliant on examiner training.

2.2 Innovating the Early Detection Mechanism

With the limitations associated with the conventional methods to provide a feasible solution for early detection of CP, research has focused on more innovative ways to capitalize on natural infant behavior for diagnosis. One such effort was the design of the SmarToyGym by Goyal et al. [6]. Their design consisted of a gym with toys that were designed to study infant reaching and grasping movements by both hands and legs. The toys embedded pressure sensors, IMUs and a Gyroscope that are used to provide data to qualitatively and quantitatively study infant reaching, grasping and frequency of reach and contact duration for CP diagnosis. These metrics were identified based on infant behaviors that are formed by a certain age. Grasping for example develops among typically developing children around 4 to 5 months of age and is solidified by the time they are 8 months old [6]. Similarly reaching develops around the age of 3 to 4 months among typically developing infants. Initially the infants reach for objects with both hands but this behavior transforms to reaching with a single hand as infants grow. Premature infants tend to reach with both hands more often. The toys were also equipped with audio and sensory stimuli to grasp infant attention.

The results for the SmarToyGym studies have, so far, only been carried out on typically developing infants at low to moderate risk of CP as determined by the Bayley Scale of Infant Development. The results only verified that the metrics identified such as reaching and grasping among infants are good discriminating markers as the youngest infant tended to displace the toys further whereas the older infants reached for and grasped toys more frequently and for a longer duration. However, despite the setup similarity between their study and our research, where both capitalize on using modified toys with audio and sensory stimulus, our setup differentiates itself by designing these stimulus to utilize them not only for grasping attention but to encourage kicking movements through a goal and reward based design.

Another study by Shivakumar et al. [9] used the above mentioned SmarToyGym and a 3D stereo camera setup to study infant motion. The stereo camera set up was designed to enable infant motion studies to be completed through wireless video as well as remove the need for any special clothing with sensors other than a blue onesie to improve the imaging of infant motions. The 3D stereo camera setup allowed for tracking and classifying limb movements. However, limb occlusion created difficulties with limb tracking. Once again, the early detection methodology has only been tested with typically developing infants and their activity classified as minimally active, active or very active. Approximate

Entropy (ApEn) was used to classify activity. ApEn is a measure of the complexity and unpredictability of infant movements with healthy infants performing high on both factors. Infants were also assessed on the frequency of interaction with the SmarToyGym toys. Healthier infants were expected to interact more frequently because of the ease associated with motion. Two of the three infants, in the study were exposed to toys and scored higher on the ApEn than the infant who was not introduced to toys. The researchers expect that infants with CP will have ApEn scores in the range of or below the ApEn score of the infant not introduced to toys. However, further study is needed to validate the efficacy of their set up for CP diagnosis.

The setup of the above two studies is a step towards finding innovative solutions towards CP detection, but they still lack sufficient testing to validate the hypothesis of the researchers. However, their use of toys and setup in the natural environment of the infant also validates our design of using a crib mobile for engaging infants and encouraging kicking for CP detection. However, as mentioned above our design focuses on using the stimuli more actively rather than just as positive reinforcement.

Research conducted by Serrano et.al. [10] also focused on designing a semiautomated system that could be used to record and study infant leg motion by studying the joint trajectories of an infant's leg. The research used a Kinect Camera , which allowed for an affordable solution that could be used in the infant's home to record and study infant movements. Images of infants lying in a supine position were processed to extract infant leg point clouds to differentiate infant movement from their surroundings. Robust Point Set Registration was used to fit an articulated model to the infants extracted leg point cloud. Then kinematic models similar to a robotic arm were used to determine the knee and ankle joint angles and their trajectories. The system was tested on a humanoid robot which was programmed to mimic infant kicking movements. The trajectories were estimated with a relative error of 2.5% for knee and 2% for the ankle movements.

Due to the extraction of infant point cloud from the surroundings, the experimental setup allowed for the presence of an infant's parent near the infant while the testing took place. A parent's presence can stimulate the infant and encourage them to kick more frequently. Whereas, Serrano's experimental design for early detection provided a novel solution for detecting infant leg motion and kicking, there were no recommendations on how to encourage the infant kicking besides the allowance for the presence of a parent. Also further research needs to be done to ensure the effectiveness of the model with respect to human infant kicking.

Another research effort focused on detection and diagnosis of cerebral palsy in the infant's home environment was carried out by Bryant et.al [12] The design of this research capitalized on a crib mobile that was interfaced to a mobile app through Wi-Fi. The mobile app was designed to interface with the TexasInstruments CC2650STK SensorTag attached to the leg of a humanoid robot. This sensor provided acceleration and gyroscope data via BLE. This data could be viewed live in the mobile app where it was further processed, analyzed and plotted as well as emailed for future reference and analysis. The humanoid program was programmed to simulate the different categories of spontaneous kicking observed in infants and described as Alternating Kick, Left Kick, Wide Kick, Left Leg Kick, Alternating Leg Lift, Low Intensity Kick and Left Half Kick. Of these categories, low intensity and half kicks were characteristic of atypical kicking among infants. A threshold to identify infant kicking through sensor data was determined by calibrating the sensor on a human infant. The infant's parent was asked to hold the legs of the infant down for 10 sec and then asked to encourage the infant to kick for 10 seconds. This data was then used to compute the mean and standard deviations of the two 10 second intervals allowing for upper and lower thresholds to be determined. When the humanoid robot kicked above this threshold, a kick was recorded and the mobile started spinning. The results showed that the system design was able to detect 80 % of leg specific and 94% of significant kicking variances. However, the frequency of accurately detecting atypical movements was lower than detecting typical kicking patterns.

To continue along this path of innovation, this research also proposes a novel design based on principles of affordability, ease of use, and environment enrichment however, the design completely relies on movement of the mobile to elicit kicking from the infant. Our crib mobile design relies on using the three different stimulus to study their effect on infant kicking. Furthermore, the calibration of the threshold, in [12], relies on help from the infant's parent and can therefore, be dependent on training or proper execution of instructions by the parent.

Another research that integrates the use of a mobile system with detection of infant kicking is by Rogers et.al. [13]. Their design consisted of a sensor suit, a mobile and a GUI, keeping in mind affordability and technical requirements such as accuracy of hip and knee joints to 10 degrees, ease of data collection and analysis as well as a method to elicit kicking from infants. The suit was made of variable resistors as sensors, which changed output voltage based on their bending, placed in pockets at hip and knee to determine the joint angles. An Arduino Mega 2560 R3 was used to read and collect sensor data as well as control the mobile based on the kicking pattern of the infants. When kicking was detected, the mobile was turned on and it turned off when the kicking dropped as determined by the sensor data. The GUI was designed to allow for easy control of the system setup such as turning mobile on or off, processing and viewing data plots.

The system was tested on a 3 month old infant and, in order to determine the accuracy of sensor data from the suit, it was verified against motion capture technology and visual reconstruction software to determine the accuracy of joint angles. The accuracy of the sensor in detecting the frequency and relative amplitude of kicking was found to be similar to that of the visual reconstruction software. If the change in the hips joint angle was greater than 5 deg/s than the controller would turn on the mobile and stop the mobile if it was less.

Their work therefore, provides a simple design to study motion in infants and can be useful in detecting delayed movement development. However, the paper simply references the connection between mobile movement and infant kicking and does not state if this was indeed observed with the test subject. Furthermore, the research only qualitatively mentions the accuracy of their design by comparing the results with an existing motion sensor technology and provides no quantitative analysis as to the degree of accuracy of the system in detecting infant kicking independently and with respect to the motion capture system. Once again, the design still needs to be verified on a larger pool of infants to solidify the results of the research.

2.3 Crib Mobile and Infant Memory Learning

The mobile crib is a widely used paradigm in studying infant learning and memory capabilities. Infant learning studies are crucial to understanding infant psychology in order to validate the experimental design of future research that focuses on behavioral modifications among infants. Research shows that infants are capable of forming new memories and learning as early as 2 months of age [16]. Therefore research by Sargent, Reimann, Kubo and Fetters [14] focused on quantifying this learning in infants by using a discovery learning task. For this purpose, infants at the age of 3 to 4 months were introduced to a crib mobile without establishing any association between their motion and crib mobile movement and music playback. The infants were laid in a supine position with LEDs and rigid bodies mounted on a platform in order to study infant motion through video recording. The metrics used to quantify learning among infants were 1) percentage of reinforced leg action (%RLA), which is defined as the duration of mobile activation, 2) positive variance of end effectors, hip-knee angle correlation coefficients and 4) hip and knee joint torques. The testing was done over a period of two days. On the first day the testing consisted of the baseline and acquisition stages. On the second day, the testing consisted of baseline, acquisition and extinction stages. Baseline was a 2 minute stage during which no feedback from the mobile was given and the spontaneous kicking of infants in supine positions was measured through sensors attached to the body in order to calculate a vertical threshold value unique to every infant based on the height of the feet during kicking. This threshold value was measured as one standard deviation above the mean height of both feet. The acquisition phase, which lasted six minutes, consisted of three two minute intervals, during which the mobile crib played music and rotated for three seconds whenever the left or right feet crossed the vertical threshold. After three seconds, the mobile was retriggered only if the infant kicked past the vertical threshold again. The extinction phase, which was exclusive to the second day of testing, was conducted without feedback from the mobile and infant behavior studied for three minutes.

Infant motion was studied to evaluate infant performance and learning based on %RLA. If the %RLA was 1.5 times higher than the baseline period during any 2 min acquisition period then the infant was considered to be successful at performing the task. If the %RLA was 1.5 times or greater than % RLA of baseline day one during the 6 min acquisition period of day two then the infant was categorized as a learner. The infant's state of attention and arousal was also coded for each two minute interval. Testing was carried out on 20 infants of whom eight were identified as learners and 12 as non-learners based on these metrics. Even though, learners were categorized by an increase in %RLA , they initially decreased their %RLA as a response to being introduced to the mobile i.e. as a novelty effect of being introduced to the mobile, and then strategically to understand the correlation between their movement and mobile. An analysis of the position variance of end effectors was used to determine how and what infants learned. Infants for whom a high threshold value was used, (i.e. over 50% of the infant leg length) learnt the height of the trigger which they displayed by reducing the variation of their feet and moving closer to the vertical threshold. On the other hand, infants with a low threshold, (i.e. below 50 % leg length) showed greater variance in kicking, indicating that their learning outcome was to increase kicking frequency. A typical infant's kicking pattern showed synchronous hip-knee flexion. However, this correlation was reduced in infants who learned more efficient ways for triggering the mobile based on the vertical height of the threshold and this was observed in the learners group. Infant who learnt the association between their kicking and mobile movement displayed large high and knee torques during the extinction period on day two, indicating attempts to reactivate the mobile.

This research provides some evidence that infants are capable of making associations between their motion and a novel task such as the rotation of a crib mobile even when they are not introduced to the task beforehand. However, it also highlights, as seen by the group of non-learners that learning and association are relative even among healthy infants and there is a need for a longer and more detailed study to determine how learning is acquired among healthy and preterm infants. This research was also conducted in a lab setting and therefore, a more robust design that allows for testing to be carried out in the home environment, as seen in some of the earlier studies, is needed if the results are to be extrapolated to testing for early detection of neuromuscular disorder such as cerebral palsy.

Another study that utilized the mobile paradigm to study associative learning, short term and long term memory, among infants between 2 to 6 months of age was conducted by Heathcock, Bhat, Lobo and Galloway [15]. The study was designed to investigate, firstly, how learning and memory takes place among term born infants exposed to the mobile paradigm as opposed to a comparison group and secondly to determine how preterm infants, with a gestation age of less than 33 weeks and weight of less than 2500g, show memory and learning when introduced to the mobile paradigm. For this purpose, three groups of ten infants, with no known disability or illness, were assigned to one of the groups- term born infants exposed to the mobile paradigm, comparison group with no association between infant motion and mobile feedback, and preterm infants introduced to the mobile paradigm. The study was conducted over a period of one week for the term born and comparison group but over a period of six weeks for preterm infants based on earlier research that found preterm infants did not show learning and memory within the first week of the mobile paradigm. Each week the testing was done on Day 1, Day 2 and Day 7 to test for learning, short term and long term memory respectively. Each day the testing session consisted of fifteen minutes of testing. The fifteen minutes were divided into sections of three minutes each and each section was coded for kicking. The sessions were defined as baseline period (three minutes), acquisition period (three sessions of three minutes) and extinction period(three minutes). A kick was defined as a simultaneous extension of hip and knee of 15 degrees or more.

Term infants were tested for learning on day one, short term memory on day two and long term memory on day three. Learning was said to have occurred if the kicking rate of the infant was higher in extinction period than the baseline period when there was no feedback from the mobile following acquisition, and if the kicking rate during extinction was higher as compared with the comparison group. Short term memory was exhibited by infants if the normalized kicking rate during baseline was higher on day two than on day one as determined by ANOVA and if the normalized baseline kicking rate was higher than the normalized baseline kicking rate of the comparison group. A similar measure was used for long term memory on day seven of the same week for term infants and day one of the next week for preterm infants.

Preterm infants were observed to kick more frequently than their counterparts. However, unlike infants in the full term group, preterm infants did not display associative learning or short term and long term memory, despite the longer round of testing, by failing to meet the criterion for these traits. Infants in the full term group exhibited all three characteristics. This provides some evidence that infants born full term versus preterm exhibit differences in associative learning and memory with respect to the mobile paradigm. It may be because infants born preterm are at risk of sensorimotor and cognitive impairments which are required to form associations between self-motion and mobile movements. Furthermore, preterm infants also exhibit difficulties with visual attention and perception as well as regulating arousal. Therefore, this study highlights valid concerns with respect to the use of the mobile paradigm in early detection methodologies. However, the small size of the group tested limits the generalizability of the results. Furthermore, there is a need to investigate if the mobile movement is in fact likely to cause over stimulation among preterm infants affecting performance and, if so, can other stimuli be used to achieve better performance? Answering these questions can be critical for designing a valid method for an affordable, early detection system that can be deployed in an infant's home and without requiring clinical or medical expertise.

A similar experiment, using the mobile paradigm was also conducted by Haley, Weinberg and Grunau [16] in order to determine the effect of cortisol on learning and memory among infants. Their tests consisted of baseline, acquisition and extinction periods and videotapes of test sessions were coded to determine if learning and memory had taken place. An infant pool consisting of 24 preterm infants with a gestation age of less than 32 weeks and 18 full term infants of corrected age of three months was tested for the effect of cortisol secretion. A kick was considered to be a smooth, continuous motion of the foot in either the vertical or horizontal position. Learning was evaluated on two metrics. The first metric calculated the relative learning ratio for day one, which was defined as the kicking rate during learning of day one with respect to the baseline kicking rate on day one. The relative learning ratio was calculated for day two which was the kicking rate during training on day two with respect to the kicking date during baseline day one. Learning and memory were evaluated using the relative learning ratio for day two. Another approach to define learning was if the kicking rate during training was 1.5 times higher for two consecutive minutes with respect to the baseline. Short-term memory was evaluated through relative kicking rates during extinction phase on Day one and Day two. For long-term memory, a baseline retention ratio, which compared kicking from baseline day one with kicking during baseline day two was used. The study concluded that learning and memory were more evident in infants who showed an increase in cortisol secretion from pre to post testing and that a moderate level of cortisol concentration was more beneficial for both memory and learning. This association between infants was concluded despite the fact, that of the groups studied, cortisol increase was observed among sub groups of both preterm and term infants.

This study demonstrated learning even among preterm infants, which suggests that a deeper understanding of what qualifies as learning in infants needs to be made. The use of the mobile paradigm in a neurological study shows that the mobile paradigm is widely used in determining infant behaviors. Its ubiquitous nature, therefore, makes it a powerful tool in determining infant psychology and behaviors and designing experiments that can capitalize on those results to achieve breakthroughs in early detection and intervention of neuromuscular disorders among infants.

Another study by Yu-Ping Chen, Linda Fetters, Kenneth G. Holt and Elliot Saltzman [17] builds on the evidence that infants demonstrate learning by modifying their spontaneous kicking to complete a goal when motivated by positive reinforcement. Despite the ability to learn, some infants may need a conditioning period, where they are introduced to an easier task in order to form the correlation between their movements and positive reinforcements whereas, other infants are capable of forming the association without any prior introduction. It also aims to explore how mobile reinforcement paradigm can be used to encourage behaviors among infants that may not have yet fully developed among infants such as out of phase kicking.

In their experiment, 4 month old healthy infants were laid in a supine position and a panel was mounted at the height of the infant's leg when the hip angle was 30 degrees, such that kicking the panel would result in a mobile movement. In order to encourage out of phase kicking movements, the panel was mounted such that the out of phase kicking would provide the most direct contact path between the panel and the foot and would therefore be the most efficient way to turn on the mobile. The mobile activated when the foot made contact with the panel, would remain on while the contact was sustained, and turned off when the foot left the panel. The hypothesis was that, because of the mobile reinforcement, infants would increase kicking frequency exhibiting learning, and that there would be decreased in-phase kicking when there was (1) contact between foot and the panel irrespective of mobile reinforcement and (2) mobile reinforcement irrespective of whether the panel was contacted or not.

This study also aimed to determine the effect of weight in correlation with the development of out of phase kicking. In a second experiment, a weight equal to 5% of the infant's leg mass was added to the ankle in order to study the effect on kicking patterns. It was hypothesized that, because of weight, infants would produce more in-phase kicking as the synchronous motion would reduce the muscle force required to contact the panel.

The experiments were recorded using two OPTIOTRAK 3020 motion analysis system sensors. The mobile was augmented with a small chime to introduce both a visual and auditory stimulus to the infant's environment. Each experiment consisted of a 2 min baseline, where no mobile reinforcement was given. The baseline period was followed by a one to two minute guidance period, in which infant left and right legs were separately guided to touch the panel so infants could form the causality between panel contact and mobile movement. There was an 8 min acquisition period, during which the mobile activated whenever the infant made contact with the panel. This was followed by a four minute extinction period, during which the mobile reinforcement was discontinued. The data analysis, for the sake of consistency, was conducted in 2 min periods.

A kick was identified when there was continuous leg movement such that there was motion for five continuous frames or the hip and or knee joint angles changed by more than 11.5 degrees. A kick was categorized as a 'contact kick' when the foot touched the panel or as 'no-contact kick' when there was no contact with the panel. Learning was concluded if the group performance was above the baseline levels as well as if infants individually kicked at a rate of at least 5 times higher in any two consecutive minutes compared with their respective baseline levels. The Pearson Correlation Coefficient was used to determine the hip and knee joint angle correlation. A high positive value meant more in-phase kicking and a more negative value indicated more out of phase kicking pattern.

Infants in Experiment 1 met the learning criteria by increasing their percentage of contact kicks (%CK) by at least 1.5 times in at least one of the 2 min intervals of the acquisition period. However, the learning effect did not last during the extinction period. During the acquisition period, contrary to the hypothesis, there was an increase in in-phase kicking during mobile reinforcement. However, as hypothesized, the contact kicks were less in-phase than the no-contact kicks.

Infants in Experiment 2 had weight cuffs during the acquisition periods but not during the baseline and extinction periods. Once again participants met the learning criteria by increasing the %CK frequency to at least 5 times higher in one 2 min period as compared with the baseline. However, unlike the infants in Experiment 1, there was a significant increase in contact kicks as compared with baseline in the first two minute interval of the extinction period, demonstrating learning. This however did not last towards the end of the extinction period. Once again, the no-contact kicks were more in-phase during the acquisition period as compared with baseline and extinction. Contact kicks were again less in-phase than no-contact kicks.

This study concluded that infants as young as 4 months of age are capable of demonstrating learning. Enriching their environment with more cues, such as the addition of weights could encourage the acquisition and retention of tasks as demonstrated in Experiment 2. The second hypothesis that the panel angle would facilitate contact kicks which are less in-phase was also proven. The third hypothesis that suggested a decrease in in-phase kicking through mobile reinforcement was disproven. This may be because of an inclination to favor the more developed movement i.e. in-phase kicking when kicking at increased frequency. However, there was a change in infant kicking pattern during the extinction period that lead to an increase in more out of phase kicking as compared with baseline. This showed that an increase in kicking between baseline and subsequent intervals may not be a sufficient criteria to quantify learning as the infant response to modify behavior during extinction to induce the desired response is also suggestive of learning.

Therefore, this study also looked into the association between the mobile paradigm and learning and determined the effect of additional environmental cues such as the addition of weights to the ankles on infant learning. It also highlighted how the same mobile paradigm may be used to encourage more advanced motions such as out of phase kicking and suggested some limitation of using the widely used 1.5 times the baseline kicking criteria to conclude learning.

CHAPTER 2. DESIGN CONSIDERATIONS

Studies analyzing the effect of early intervention among infants with developmental disorders underline the importance of conducting the intervention in their natural environment. As suggested by Bradshaw, Steiner, Gengoux and Koegel [2] who reviewed the effectiveness of early intervention among infants at risk of autism spectrum disorder, interventions delivered by parents at the infant's home allowed for greater infant-parent interactions. Their review of intervention studies also utilized integration of a reward system to encourage the infant's efforts. The research also found that any intervention method should target infants behaviors such as attention, motivation and playfulness. Research by Morgan, Novak, Dale and Badawi [1] developed GAME to capitalize on the effect of brain development in infants as a result of environment enrichment. Other studies such as by Goyal, Torres, Rail, Shofer et.al.[6], aimed at early detection of cerebral palsy, also emphasized the need to capitalize on a natural infant play environment when designing detection and intervention methods for infants. A review by Morgan et.al [11], of the studies aimed at improving motor outcomes for infants with cerebral palsy concluded that environment enrichment showed a small positive correlation between environment enrichment and motor response among infants. This warranted more studies to determine the effect of environment enrichment and motor response among infants with cerebral palsy.

Therefore, keeping in mind the emphasis placed on utilizing the natural environment of infants we chose to design our research methodology for testing the effect of stimuli on infant behavior using a crib mobile. As discussed above, the crib mobile has been used earlier to study the effect of reinforcement on infant learning and therefore, proved a natural choice for investigating the effects of different stimuli on infant behavior.

Another essential design consideration that we had to make was which stimuli should be included in the crib mobile. Keeping in mind the above discussion, we note that, any stimulus used must also be found in the natural environment of the infant. Furthermore, the choice of stimulus must also not prove a source of discomfort for the infant and at the same time be able to grasp the infant's attention. The stimulus should also be easy to embed in the crib mobile. Our choices for the stimuli are discussed in more detail below.

3.1 Choice of Stimulus

Our choice of using all three stimuli including visual, audio and movement stems from the presence of these stimuli in infant toys and their use as either positive reinforcement or attention grasping techniques during early intervention studies for infants with development disorders. Passetti et al. [18] used sensorized toys to study the grasping capabilities of preterm infants in order to determine differences according to age as well as the development in grasping capabilities as infants are trained with specialized toys over a period of four weeks. These sensorized toys also used LEDs in them to attract infant attention and encourage grasping. Our goal with using LEDs as part of a crib mobile will however be to use LEDs as positive reinforcement for goal attainment i.e. kicking by infants.

The effect of music on infant behavior is a more widely studied domain. Research by Zentner and Eerola [19] investigated whether infants were capable of rhythmic movements in response to music as adults exhibit when dancing with music. They further investigated if at infancy other audio sounds such as speech and infant driven speech have similar effects. They described rhythmic movements as “a movement of parts of the body or the whole body that was repeated”. Their results showed that infants are capable of exhibiting rhythmic motion to music and infant driven speech. However, this response is not exhibited when listening to regular speech. Infant driven speech is only effective in eliciting rhythmic motion up to six months of age. The results also showed that certain features in music such as pulse clarity and accelerating passages were able to solicit more and faster rhythmic movements than audio sounds lacking these features. This provides some evidence that music can be used for behavioral modification among infants by encouraging rhythmic or continuous motion such as kicking. For our design we thus use nursery rhymes, which have good beat clarity, as an audio cue in our crib mobile in order to encourage kicking. Research by Heathcock, Bhat et al. [15] investigating memory and learning among preterm infants suggested that preterm infants memory and learning lag could be a result of overstimulation of preterm infants in the mobile paradigm as they have difficulty with arousal and self-regulation. However, studies conducted by Loewy et al. [20] on utilizing music therapy for improving vital signs, feeding and sleeping in premature infants concluded that it is not necessary for audio sounds to be overstimulating to premature infants. In fact, certain elements of music therapy such as rhythm, when utilized appropriately, can be beneficial for infant growth and development.

Similarly, Walworth [21] studied the effect of music on social development among both full term and preterm infants. Seventy infant-caregiver dyad participated in the study where the infants were between 7 to 24 months corrected age. The participants were part of a thirty minute music developmental group in which they participated at least three times, each concluded with a developmental survey. The thirty minute music development was assessed on the basis of infant toy interaction. The control group was a ten minute long infant toy interaction without music. The study concluded that there were no significant differences between preterm infants and full term infants in terms of both the social and alone behaviors exhibited during toy play where social behaviors were defined as the infant engaging with the parent through toy play, gestures or vocalizations and alone behaviours referred to infant engaging in these behaviors without directing them to the caregiver. These results show that music can be a powerful stimulus in encouraging behavior modification such as increased kicking among both term and preterm infants.

Crib mobile movement has been utilized in studies such as Chen, Holt and Saltzman in [17] and Haley, Weinberg and Grunau in [16] to study learning and memory in infants. The mobile movement was used as a reward for positive reinforcement to infants for kicking. This allowed the researchers to study the infant capabilities in associating their actions with a goal. Since our research aims to utilize the same principle of goal and reward based mechanism for infant behavior modification, we chose to include mobile movement as one of the stimuli in our research. Furthermore, the choice of this stimulus will allow us to investigate whether there is indeed a possibility that the mobile movement can cause over stimulation and discomfort to infants.

Therefore, we will use these three stimulus, which are already present in the infant environment to encourage infants to exhibit increase in kicking activity.

CHAPTER 3. DESIGN OF MOBILE

The mobile was designed with the objective that the system should allow for ease of control and the ability to log data, making it convenient for use at home and by parents. The design also needed to be easy to transport and safe for use around infants. We chose the mobile by Transformania Toys [22] as the initial construct to design our system around.

4.1 Physical Design

The original mobile came with a detachable music box that could be placed on a crib or set up as a gym toy for the infant. We utilized the music box, which attaches to the top of the mobile, and augmented its structure in order to have electrical circuitry for all three stimuli. The musical box has three LEDs attached to it. The top LED (the hat) was removed in order to allow for power and signal connections from a battery and a microprocessor namely the Raspberry Pi 3B+. The mobile came with three plastic toys coupled with the music box. Figure 1 shows the mobile set up for experiment.

Figure 1. Mobile Physical Design

When assembled in the above configuration, the mobile has dimensions of 18 by 20 by 23 inches. Each of the legs of the mobile are at a distance of 18 inches from each other. The hanging toys are at a height of 11 inches from the floor. The assembled product, as per the manufacturer details, has a weight of 3.13 lb.

4.2 Software Design

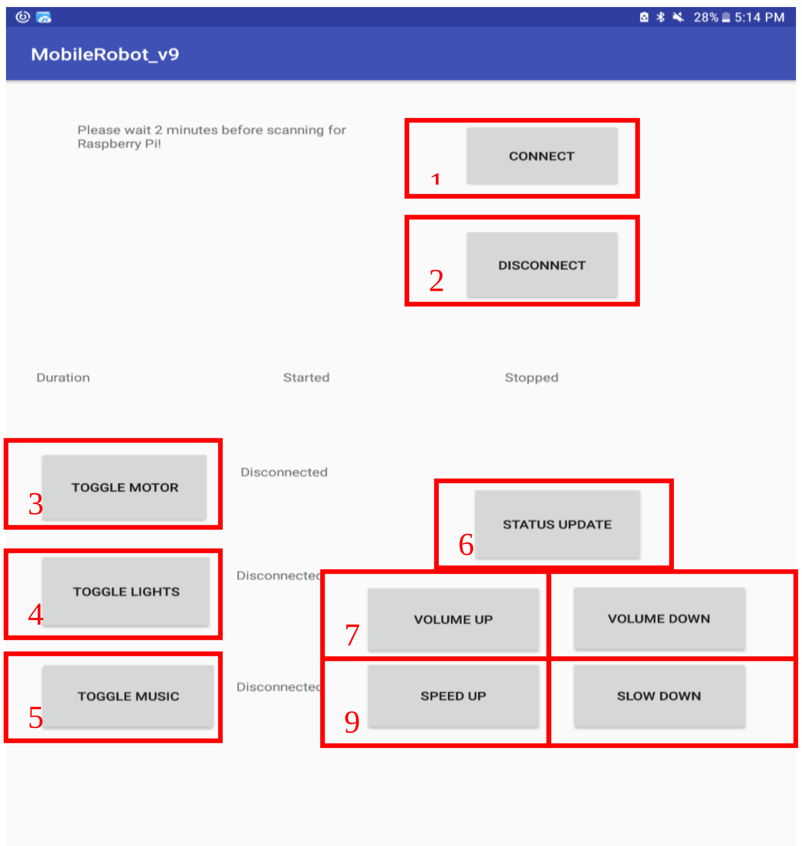


Figure 2. Android Application

The software design, once again, was focused on making the system easily operational within the infant's home environment so that the data can be gathered and tests conducted without requiring technical and expert knowledge by the caregiver of the infant. For this purpose, we designed our control application on the Android operating system platform which according to [24] runs on roughly 75 % of the mobile devices worldwide. Effective control of the three stimuli in the crib mobile would require an effective communication between the control application implemented on the tablet and the Raspberry Pi 3B+. The GATT communication implemented is shown in Figure 3 and discussed in detail below.

Table 1. Android Application Description

Label	Description
1	Starts the Scan for Ry Pi and connects on discovery
2	Disconnect when you no longer wish to maintain the BLE connection
3	Use it to turn motor on/off
4	Use it to turn lights on/off
5	Use it to turn music on/off
6	Use this to get a status of all Stimuli
7	Use this to increase the volume of the music
8	Use this to decrease the volume of the music
9	Use this to increase the motor duty cycle but turn motor off first
10	Use this to decrease the motor duty cycle but turn motor off first

The control application running on the tablet was designed to run the GATT client which will 1) scan for the microprocessor and connect to the GATT server and 2) control and display the status of the three stimuli. Because the control implemented thus far for all three stimuli was on/off control the control application, layout shown in Figure 2 and Table 1, used buttons to toggle the state of the three stimuli. All three stimuli could be turned on or off independent of each other. Each time any stimulus was turned on the control application recorded the data and time the stimulus was activated. When the stimulus was turned off the control application noted the duration for which the particular stimulus was activated. This allowed us to match the instance of stimulus activation with infant kicking.

The control application can also adjust the volume of the audio stimulus in real time from 45 decibels to 52 decibels. We used this tuning capability to adjust the volume of the audio stimulus to a level most appropriate for each infant in consultation with the caregiver of the infant so that the volume did not become a source of discomfort for the infant. We however, did not use it as an independent variable for studying infant kicking activity and behavior modification. The application also allowed to adjust the mobile's speed of movement during the experiment. However thus far, we have not used this feature as an independent variable to study its influence on infant kicking. The mobile has a rotation speed of 5.5 rpm however, with the control this can be increased to 10.17 rpm.

The control application allowed the user to request status updates of the three stimulus using the status update button. This allowed for an increased mobility to the user in a home environment.

4.2.1 GATT Central

The GATT central was implemented on an Android tablet. When connect was pressed it initiated a scan for nearby BLE devices and the mac address of the Raspberry Pi was identified then a connection with the pi initiated. The GATT Peripheral running the server, accepted this connection, allowing for a flow of information to take place.

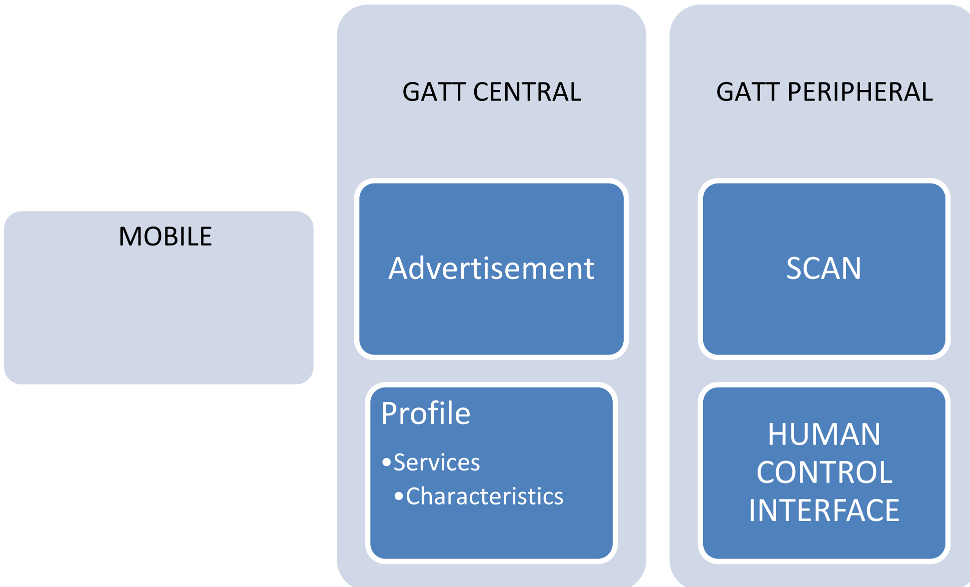


Figure 3. GATT Communication

4.2.2 GATT Peripheral

The GATT peripheral was implemented in the RPi using the publicly available Bluez Library at [23]. The RPi was programmed to run the GATT-advertisement and server after 2 minutes of boot up allowing for the necessary Bluetooth modules to be loaded. The running advertisement broadcasted the advertisement data which let the central device know of the type of data available and its value. Therefore, the peripheral implemented the GATT transaction profiles, services and characteristics available and advertised them. The GATT profiles are a predetermined collection of services set by the Bluetooth SIG. The example-server set up in [23] was modified to run a custom service with a custom characteristic that allowed a read and write to turn on and off all stimuli and allowed the user to get a status update of the state of the three stimuli.

4.3 Electrical Design

The original circuitry of the music box was removed and the dimensions of the PCB mounting space available measured. The microprocessor for this setup was a Raspberry Pi 3B+ that was used to provide the control signal to each of the three stimuli end effectors namely the LED's, a motor and speaker. The LED's in the original mobile were replaced with Adafruit's LED's that would be better visible inside a room. A new PCB was designed where the controllers for the motor, speakers and LEDs were integrated with the RPi. The final schematic images are shown in Figure 4 and Figure 5.

Adafruit's Max 98306 a Class D amplifier, which is a high efficiency amplifier, was used to regulate the speaker. The audio signal was transmitted from the Raspberry Pi to the Max 98306 amplifier which then passed the signal on to an 8 ohm, 1 W toy speaker. A small DC motor for toys similar to the one available at [25] was controlled by means of the Adafruit's L293D H-Bridge Motor Driver for DC Motors. A pull down resistor was used

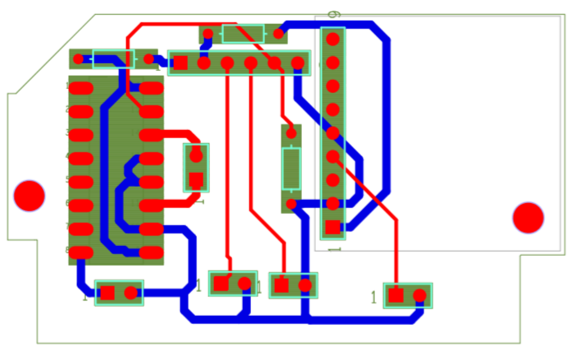


Figure 4. Electrical Design Layout

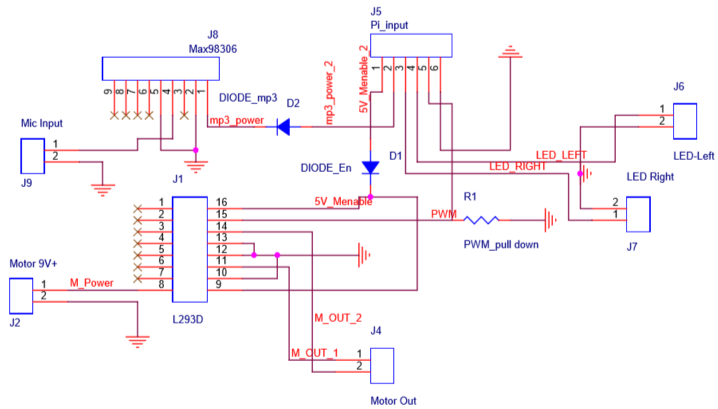


Figure 5. Electrical Schematic

at the enable pin to keep any noise from activating the motor in the absence of a control signal from the RPi. This behavior was observed when the mobile was run with the first iteration of the pcb that lacked the pull down resistor and used separate sources for powering the RPi and the pcb. The power source was later also changed to the TalentCell Rechargeable 12V power bank which met the 12V power demand for powering the L293D motor controller and the 5V output supply for the RPi.

The electrical wiring was done between the RPi, the power bank and the pcb of the music box. Wiring of length 20 inches was used to ensure that the controller and the power bank could be placed outside the reach of the infant as they are laid in a supine position.

CHAPTER 4. EXPERIMENT DESIGN

In order to verify our hypothesis the mobile was tested with infants between 2 to 4 months of age. All tests were carried out at the infants own home under the supervision of a parent or guardian. The experiment protocol was designed in consultation with Dr. Yuping Chen, who is an Associate Professor of Physical Therapy at Georgia State University. This was to ensure that the protocol complemented the mobile design and that the protocol did not become a source of distress for the infant. The details of the experimental setup and the protocol are discussed below.

5.1 Experimental Setup

a. The mobile crib was assembled on top of a flat surface, such as a floor or table, with a blanket placed on it for infant's comfort. The flat surface measured at least 3 feet by 3 feet to allow sufficient space for the mobile setup and infant motion.
b. The battery and the RPi were placed at a safe distance from the infant in a secure space keeping in mind that they did not interfere with infant motion. The setup allowed for the battery and the RPi to be placed at a maximum distance of 20 inches away from the crib mobile.
c. The mobile was then powered up by completing its electrical set up with the battery and RPi as shown in Figure 6.

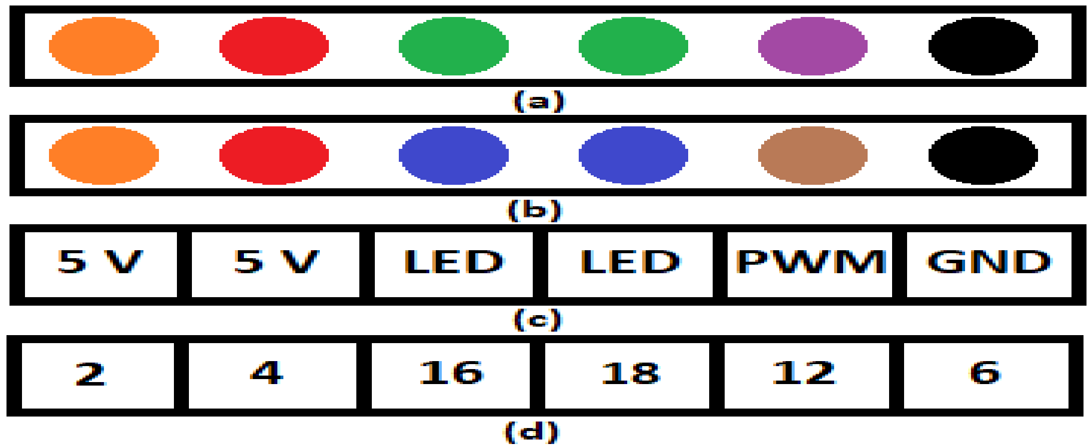


Figure 6. Electrical Connection Diagram. (a) Mobile connection color codes. (b) RPi connection color code. (c) Pin identification. (d) RPi pin configuration.

d. The electrical set up was verified and the mobile powered up. It took roughly two minutes before the RPi would boot up and become available to connect through its BLE connection.

e. During this time the experiment protocol was explained to the parents. In order to keep the infants from becoming fussy a parent was allowed to be present close to the infant's head side. However, the parents were not allowed to interact with the infant unless the infant became distressed and needed to be soothed. This ensured that infant activity was not influenced by any other stimuli other than those integrated in the mobile.

f. If audio stimulus was being applied during the acquisition then the appropriate volume for the infant was decided by consulting with the parent.

g. The infant was then placed under the mobile such that the music box of the mobile was roughly at one-third of the infant's body length from the head as shown in Figure 7. This was to ensure a good line of sight of the mobile.

h. Videos of infant activity were recorded through a tablet or camera device placed at about one feet from the infant.

5.2 Experimental Protocol

Each infant was tested with three distinct conditions. The baseline condition involved the introduction of the crib mobile to the infant but did not use any stimulus in response to the infant kicking. The baseline phase was a total of 1 minute long and served two purposes:

1. To serve as a control for each individual infant's kicking without stimulus.
2. Take away some of the novelty effect of being introduced to a new crib mobile.

The baseline period was followed by the acquisition period which was a total of 3 minutes long. During the acquisition period each infant was introduced to one of the three stimulus of the crib mobile every time they kick. The reinforcement lasted for 5 seconds every time the infant kicked and continued as long as they kept kicking. That is the reinforcement was only stopped if there was no kicking within 5 sec following the last kick. The purpose of the acquisition phase was to introduce the stimulus and study its effect on the infant. The acquisition phase was followed by the extinction phase which is the same as the baseline with no stimulus feedback and 1 minute in duration. This phase was required to see if there was any carryover effect of the stimulus feedback if the stimulus was removed.

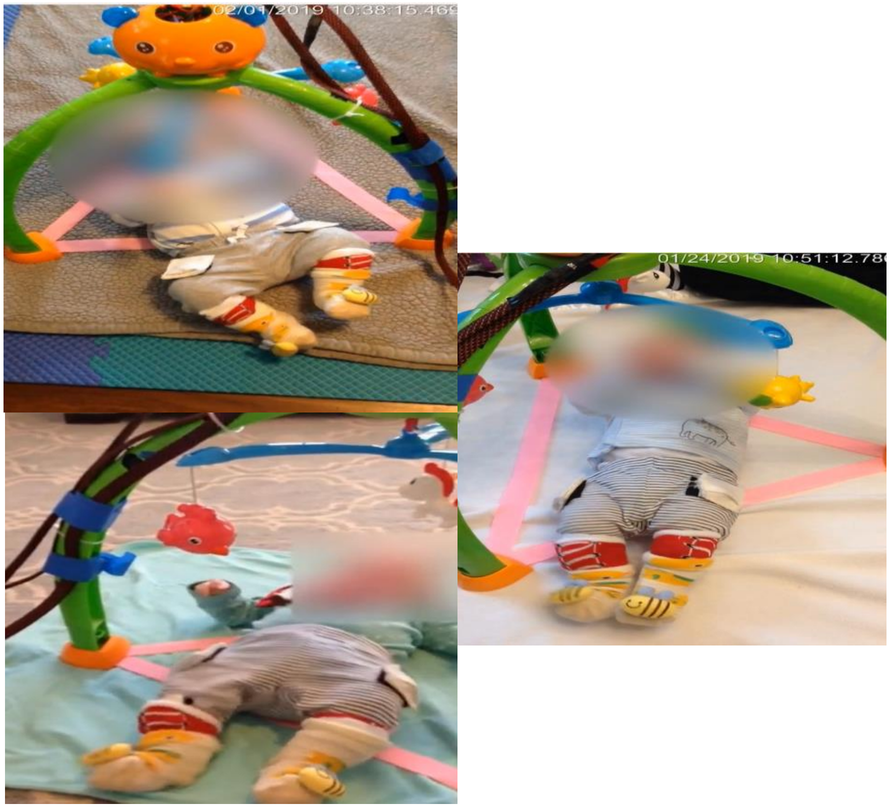


Figure 7. Infant Testing Sessions for All Three Stimuli

5.3 Data Processing

In order to study the influence of each stimulus on infant behavior the recorded videos were processed and encoded by three independent coders. Software developed as part of the research into early diagnosis of CP being conducted by Fry et al. [28] was used to codify these videos.

Research by Fry et al.[28] focused on designing a sensor suit which can accurately qualify infant motion as kicking or not kicking. For this purpose, the sensor suit was embedded with 6 axis IMU sensors (MbienLab's MetawareC). A sensor was placed on the thigh, shin and foot of each leg to gather movement data. The data from these sensors was collected over BLE through a custom app. The Stance Hypothesis Optimal Detector (SHOD) was used to detect activity from the IMU acceleration and angular rate data. The sensor data was fused using either the OR method or MODE method. The OR method identified kicking by a leg if any of the sensors on the leg detected kicking. The MODE method identified kicking if 2 or more sensors of the same leg identified kicking.

In order to validate their activity detection method Fry et al. constructed the truth data through video processing done through the custom app. Each video was split into shorter videos of 30 seconds. The videos were then slowed down to be one minute long. The coded data of the three coders was once again consolidated based on the MODE method at each time instance.

Fry et al's results concluded that the MODE method for sensor fusion tended to have higher sensitivity but lower specificity than the OR method. We used the video coding data processed by Fry et al's to develop truth about infant kicking as the data to base our analysis of kicking kinematics on.

CHAPTER 5. KICKING KINEMATICS

In order to verify the effect of the three different stimuli on infant behavior, infant kicking kinematics were studied. The choice of kinematic variables to assess kicking behavior was selected based on earlier research conducted to identify infant kicking dynamics and their characteristics among term and preterm infants in determining the variables associated with at-risk infants. These kinematic variables and their associated differences during the baseline and acquisition period were used to determine if and how the stimuli added to the mobile affected these kinematic variables.

In [30], Trujillo-Priego and Smith used triaxial accelerometers as wearable sensors to study infant kinematic motion over a full day of infant motion. They quantified kinematic variables of duration, average acceleration, peak acceleration and type of infant leg movements in their study. The three types of infant leg movements identified were unilateral, bilateral synchronous and bilateral asynchronous. Kicking was identified as unilateral if only one of the infant legs moved. It was quantified as bilateral movement if both legs moved at the same time however, the movement of both legs was considered to be synchronous if the kicking for both legs started at the same time and asynchronous if the legs did not start kicking at the same time. A new leg movement was quantified whenever the infant leg paused or changed direction. The duration of movement was calculated using sample counts from sensor data.

The study was conducted with infants between the ages of 1 to 12 months of age. The data was collected through wearable sensors which were placed on the infant’s ankle by making the infant wear socks with Velcro on them and covered again with a sock. This allowed data to be collected throughout the day for 8 to 13 hours per day. The wearable sensors allowed the data to be collected in the natural environment which further facilitated a more complete study of infant movement which is diverse and cannot be completely studied in short periods of time. Each infant was visited three times and data collected using inertial sensors (Opals, APDM) which synchronized the accelerometer, gyroscope and magnetometer data at a sampling rate of 20 Hz. Each infant's developmental progress was also determined using the Alberta Infant Motor Scale (AIMS) and the infant's weight, length and head circumference were also measured.

The Pearson correlation coefficient was used to determine the inter-leg correlation for duration, peak acceleration and average acceleration. The test showed high correlation between data from the left and right legs. Therefore, the authors only analyzed the right leg data. The linear mixed model effects was used to determine a fixed effect over visits with a diagonal covariance matrix. The average duration was found to be between 0.23s to 0.33s. The linear mixed models did not reveal any fixed effect of visits on right leg durations. The average acceleration was found to be 1.59 $\frac{m}{s^2}$ to 3.88 $\frac{m}{s^2}$. The linear mixed models did not reveal any fixed effect of visits on right leg average acceleration. The peak acceleration was found to be 3.10 $\frac{m}{s^2}$ to 8.82 $\frac{m}{s^2}$. The linear mixed models did not reveal any fixed effect of visits on right leg average acceleration. All three parameters were studied against both the age and developmental score of the infants as infants at the same 6 months of age can be at different developmental stages.

The study verified their results for consistency with other studies that had studied these kinematic variables. Results showed that unilateral and bilateral asynchronous movements were more common among infant kicking profiles than bilateral synchronous. The unilateral kicking movements had a left and right leg mean of $\mu_L = 4875$ and $\mu_R = 5358$ respectively. The mean for synchronous kicking was $\mu_S = 11$ and for asynchronous kicking was $\mu_L = 9391$ and $\mu_R = 9427$ for left and right leg respectively. The peak acceleration from the study conducted by Gravem et al. [31] on spontaneous movements of one month old preterm infants was found to be $3.35\frac{m}{s^2}$ which was consistent with the results from this study. The average acceleration as determined by Fan et al [32] to study the cramped-synchronized general movements (CDGMs) among infants was $14.5\frac{m}{s^2}$, which was also consistent with the results from the study by Trujillo-Priego and Smith. Similarly, duration of movement calculated through this study was also consistent with the duration calculated by Heriza [33] at 0.49s of flexion and 0.79s of extension, Van der Heide [34] at 0.38s flexion and 0.41s extension and Jeng et al. [35] with 0.52s and 0.54s of flexion and extension duration respectively.

Two consecutive studies conducted by Jeng, Chen and Yau [35] and by Jeng et al. [36] also conducted a kinematic analysis of infant kicking movements in order to determine how infant kicking kinematics vary among term infants and preterm infants and later associated these variances with the age at which infants attained walking. For the purpose of these studies, the researchers investigated 22 infants with very low birth weight (VLBW) whom they divided into two groups based on their gestational age. The first group consisted of 9 infants with gestational age of < 30 weeks and the second group of 13 infants with gestational age of ≥ 30 weeks. A third group consisted of 22 full term infants. The first study [35] evaluated the kicking movements of the infants when they were at 2 and 4 months of corrected age since major motor development may be achieved by infants during these months. Four synchronized cameras were used to conduct a 3- dimensional analysis of kinematic variables including kicking frequency, spatiotemporal organization, inter-joint coordination and inter-limb coordination.

For the purpose of collecting data, infants were laid in a supine position and reflective markers placed on the infants to identify the hip, knee and ankle joints. Infant kinematics were recorded for 5 minutes however, only 20s periods of continuous kicking was used to study the kinematic variables. This study identified a kick as a flexion and extension of the lower limb such that the hip angle changed by at least 11.5° and during the extension was at least 20% of the angular displacement during flexion. A single kick was characterized by 4 phases: flexion, intra-kick pause, extension and inter-kick pause. Kicking frequency was calculated as number of kicks in a minute and expressed as cycles per minute. The spatiotemporal variables studied were kick amplitude and the four kick phases. Kicking amplitude was defined as the angle moved during hip flexion. Inter-joint correlation between hip, knee and ankle joints was determined using Fisher Z scores and Pearson product moment correlation. Interlimb coordination was defined as a measure of the frequency of unilateral, alternate and synchronous kicking. Unilateral kicks were defined as the extension and flexion of just one of the limbs , alternate kicks were defined as infant kicking where the flexion of one limb overlapped with the extension of the other limb. Synchronous kicking required simultaneous flexion or extension of the legs such that the phases overlapped.

Analysis of the results, using t-tests, analysis of variance (ANOVA) and post hoc Tukey tests showed that the groups had similar kicking frequency at 2 months of age however at 4 months of age infants with VLBW and low gestational age had a higher kicking frequency than the infants in full term and VLBW and high gestation age groups. The kicking frequency among VLBW and low gestation age increased from 2 to 4 months of age however the kicking frequency decreased for infants with VLBW but high gestation age and term infants. These differences could be contributed to differences in physical and neurological development which are in turn indicative of slow development of motor skills than the other two infants groups studied, which by 4 months of age progressed to exhibiting more complex movements and behaviors such as reaching for toys, smiling and vocalizing.

Kicking amplitude increased for all three infant groups across age from 2 to 4 months of age. However, infants with VLBW and low gestation showed a shorter flexion phase, which stayed stable up to 4 months of age as compared with the full term and VLBW and high gestation infant groups. The latter groups tended to increase the flexion phase from 2 to 4 months of age. However, these findings were contradictory to some of the earlier studies which showed no differences in flexion phases between the preterm and full term infants across ages. This inconsistency was suggested to be a possible consequence of the joint excursions used to determine the flexion and extension phases. In this study, hip excursions were used however, other studies utilized the knee joint excursions.

Inter-joint correlation was comparable among infant groups across age except for borderline high hip knee correlation for VLBW and low gestation age infant group. The hip-knee inter-joint correlation trend across age was similar and the correlation decreased across age. Interlimb coordination showed that all groups increased synchronous kicking with age and decreased unilateral kicking. A preference for a kicking pattern however was only observed in VLBW low gestational age group which displayed high unilateral frequency at 2 months of age and high synchronous kicking at 4 months of age.

Therefore, across the three groups studied, significant differences were found among infants with VLBW and low gestational age as compared with the other groups. These differences included a high kick frequency, shorter flexion phase at 4 months of corrected age, high hip-knee inter-joint correlation and dominant kicking patterns at the two ages studied showing a reduced variability in movement as compared with the other groups. These factors were then correlated with a future study in order to determine if these differences in kinematic movements had long term developmental consequences.

This latter study was conducted to verify if kinematic differences in the three infant groups could be associated with results from earlier studies that showed that there is a delay in walking attainment among preterm infants as compared with term infants. The age at which the infant attained walking was determined as the age at which they were able to take 5 consecutive steps without requiring support. Parents reported the infant's age of walking attainment which was followed by a visit by the research team to collect data for the infant.

Normal age of walking attainment, usually around 18 months of age, was set with reference to the age full term infants attained walking and the age of walking attainment was categorized as delayed if it was 2 standard deviations later than the mean. The delay in walking was considered to be mild if the age of walking attainment was between 2 to 4 standard deviations later than the mean and severe if it was later than 4 standard deviations. These definitions and the Cox proportional hazards univariate regression models were used to categorize infant ages of walking attainment. Of the 44 infants included in the study, 21 full term infants and 17 infants with VLBW had normal walking attainment. One full term infant and 3 VLBW infants had mild delay in walking attainment. Two infants with VLBW had severe delay in walking attainment. Infants were also screened through neurological examinations at 18 months of corrected age which showed that all infants with normal age of walking attainment had normal neuromotor development whereas cerebral palsy with spastic diplegia was detected in infants who showed severe delay in walking attainment.

These groups were then matched with their kicking kinematics recorded in the earlier study. This revealed that infants with mild to severe delays had increased kicking frequency from 2 to 4 months of age as opposed to infants with normal walking attainment who reduced kicking frequency across age. This may be attributed to a delay in neural development and differences in muscle tension which affect the progress of infant movements from spontaneous to fine to distal to goal directed movements. Similarly, across age, from 2 to 4 months, infants with normal walking age had increased the flexion phase whereas, those with delays had a shorter and stable flexion phase from 2 to 4 months of age. This may be due to weakened muscles that cannot provide the required force to hold the limb in place. Infants with a mild to severe delay also showed an increase in unilateral kicking from 2 to 4 months corrected age as opposed to infants with normal walking attainment. They also exhibited a preference for a kicking pattern at the 2 ages they were studied at. At 2 months of corrected age there was a preference for unilateral kicking and at 4 months of corrected age a preference for synchronous kicking. Such a distinct pattern for kicking type was absent among infants with normal walking attainment.

Therefore, the above studies outlined essential kinematic variables that can be used to study infant motion. Some of these variables include: 1) kicking frequency, 2) flexion phase duration, 3) intra-kick pause, 4) frequency of unilateral or synchronous kicking, 5) inter-joint correlation, 6) duration of continuous kicking, 7) average acceleration of IMU, 8) peak acceleration recorded by IMU and 9) kicking amplitude.

Of the variables highlighted by these studies to distinguish infant motion characteristics, we focused on quantifying whether providing stimulus to the infant through our crib mobile influences infant activity through an analysis of the following variables: 1) duration of continuous kicking (measured by the maximum and average duration), 2) kicking frequency (measured by the percentage of kicking movement as a function of the number of collected data samples) and 3) frequency of unilateral versus bilateral kicking movements (measured as the increase in bilateral kicking as opposed to unilateral kicking). These kinematic variables helped us study the effect our stimuli had on the infant movement behavior and determine if the mobile can be used to modify the complexity of motion exhibited by infants during the first few months of their life when there are crucial motor development milestones.

CHAPTER 6. RESULTS AND ANALYSIS

Three infants were tested as part of our pilot study to verify the design of the crib mobile and obtain preliminary results to study the influence of the three stimuli: a) visual: light b) audio: music and c) movement: mobile rotation, on infant kicking activity. Each infant was visited at their home once and introduced to one of the stimuli following the experimental protocol discussed in Chapter 5. These results were then used to make a case for whether our hypothesis that the achievement of the stimuli activation goal through kicking is likely to also serve as a positive reinforcement or a reward for the infant to encourage kicking behavior. The experiment protocol was repeated with each infant twice in intervals of 5 minutes each with parents allowed to hold, sooth and comfort their infant in between the two tests. This reduced the distress for the infant, allowed them to rest between the two tests and also allowed for some washout between the acquisition period of test 1 and the baseline of test 2. The assignment of the infant to stimulus was random and was based on testing each stimulus once the appointment with the infant's family was scheduled and the parental consent obtained. Since this was a pilot study, the stimuli were tested with typically developing infants under 5 months of age with no known developmental disorders. The purpose of testing the stimuli with typically developing infants was to establish a baseline influence of the stimuli on infants within this age group. The profiles of the infants are shown in Table 2.

All infants were term infants except for infant N, who was preterm and had an adjusted age of 2 months at the time of testing. In our analysis below, we define bilateral kicking as when activity was detected for both the left and right leg and unilateral kicking as when activity was detected for either left or right leg but not both simultaneously. The method to calculate the percentage of bilateral kicking and unilateral kicking from total kicking activity are shown in equations 1-4. Here K_{Li} and K_{Ri} represent the value of activity detected for left and right leg respectively, at the i^{th} sample and can either have a value of '0' or '1'. K_B and K_U represent the sum of the bilateral and unilateral kicking samples respectively. $\%B$ and $\%\,U$ represent the percentage of bilateral and unilateral kicking activity. We define N^n as the total sample count associated with 1-minute of collected data. In this case, total sample count was computed by the number of samples in the vector when the elapsed time was a mod of 60s since our samples were logged against EPOCH time later converted to elapsed time. We define percentage of kicking activity as the percentage of activity associated with the total sample count N^n (active and inactive samples) for the n^{th} protocol minute and is represented in equations 5-7. Here $\%K_L^n$, $\%K_R^n$ and $\%K_{OA}^n$ are the percentage of samples when activity was detected for the left and right legs and overall activity, defined as the logical 'OR' of the activity of the left and right leg, for the n^{th} minute of the test. K_{L1}^n, K_{R1}^n and K_{OA1}^n are the sum of samples of left and right legs and overall activity where movement was detected for the n^{th} minute of the test and given by equation 11 where s is either the left leg, right leg or the overall activity . A_s^n in equation 10 represents the activity vector for the n^{th} minute of either the left leg, right leg or the overall activity. K_{L0}^n, K_{R0}^n and K_{OA0}^n are the sums of samples of left and right legs and overall activity, for the n^{th} minute of the test, where no movement was detected and given by equation 12. We define duration of activity as the elapsed time from the start of activity until the detected activity stopped. We analyzed duration of activity in two ways: a) maximum duration of continuous motion and b) average duration of continuous motion.

Equations 8-9 represent the formulas used for calculating these variables. Here, mD_s^n and aD_s^n are the maximum and average duration of continuous kicking in the n^{th} minute of test protocol and s is either the left leg, right leg or the overall activity. Variables P_{si}^n represent continuous periods of kicking in the n^{th} minute of the test protocol and were computed as elapsed time between two consecutive $0's$ in A_s^n for the respective s.

$$K_B = \sum AND(K_{Li}, K_{Ri}) \tag{1}$$

$$K_U = \sum XOR(K_{Li}, K_{Ri}) \tag{2}$$

$$\%\, B = \frac{K_B}{K_B + K_U}\ X\ 100 \tag{3}$$

$$\%\, U = \frac{K_U}{K_B + K_U}\ X\ 100 \tag{4}$$

$$\%\, K_L^n = \frac{K_{L1}^n}{K_{L1}^n + K_{L0}^n}\ X\ 100 \tag{5}$$

$$\%\, K_R^n = \frac{K_{R1}^n}{K_{R1}^n + K_{R0}^n}\ X\ 100 \tag{6}$$

$$\%\, K_{OA}^n = \frac{K_{OA1}^n}{K_{OA1}^n + K_{OA0}^n}\ X\ 100 \tag{7}$$

$$mD_s^n = \max\left[P_{s1}^n, P_{s2}^n, \dots, P_{sj}^n\right] \tag{8}$$

$$aD_s^n = \text{average}\left[P_{s1}^n, P_{s2}^n, \dots, P_{sj}^n\right] \tag{9}$$

$$A_s^n = [1\ 1\ 1\ 1\ 1\ 0\ 0\ 0 \dots \dots 0\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 1\ 1] \tag{10}$$

$$K_{s1}^{n} = sum(A_{s}^{n}) \tag{11}$$

$$K_{s0}^{n} = N^{n} - K_{s1}^{n} \tag{12}$$

For each of these metrics, the influence of the stimulus on infant activity was considered to be significant if any of the acquisition periods showed a 1.5 times increase in activity, for that respective kinematic metric, as compared with the baseline. As discussed in Chapter 2, the metric of 1.5 times with respect to baseline was used in [14][16-17] to establish learning effect among infants. For this purpose the acquisition period of three minutes was subdivided into acquisition minute one, two and three. Each of the acquisition minutes (A1, A2 and A3) and the extinction minute (E) were then compared with baseline (B) for each kinematic variable. The results for this analysis are presented in this chapter.

Table 2. Infant Profiles

Infant	Stimulus	Age (months)	Gestational Age (weeks)	Gender
L	Audio	4.5	37	Male
M	Movement	3	39.4	Male
N	Visual	3*	35.9	Female

7.1 Results from Audio Stimulus

The audio stimulus was tested with a 4.5 months old typically developing term infant as seen in Table 2. In order to ensure the audio stimulus from the mobile was not interfered with, all electronic devices such as television present in the infant's immediate environment were switched off. The experiment was then performed as described in Chapter 5. The activity charts and graphs of the infants with respect to the stimulus activation for the two tests are shown in Figure 8 and Figure 9 respectively.

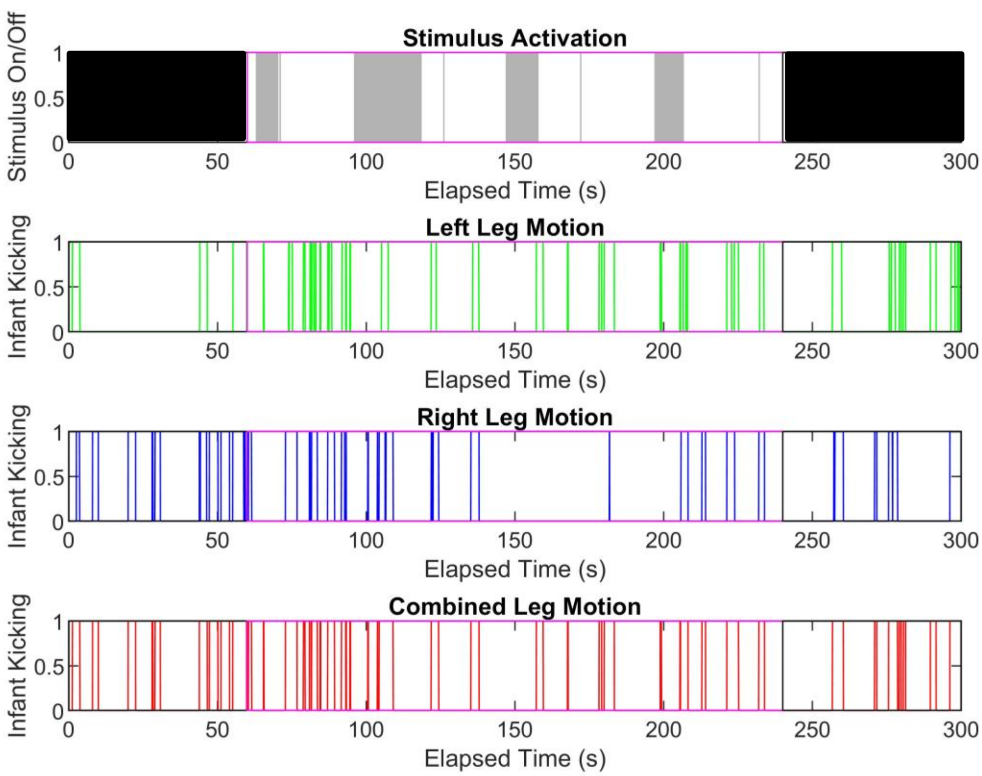


Figure 8. Audio Stimulus Activity Chart Test 1

The above activity chart segments the five minutes of test time into baseline, acquisition and extinction periods. The first black box in each subgraph highlights the baseline period, which as defined previously did not have stimulus activation. The second black box to the right in each of the above subgraphs highlights the extinction period, which again lacked stimulus activation as shown in the first subgraph. The pink box in each of the above subgraphs represents the three minutes during the acquisition periods where the stimulus was turned on/ off subject to infant activity. The stimulus is shown as activated in the first subgraph through grey rectangles and the width of these rectangles represents the duration for which the stimulus was left on after being activated based on infant motion. The second and third subgraphs in the Figure 8 represent the activity of the left leg and right leg respectively. The fourth graph represents the overall activity of the infant which is obtained by a logical "OR" of the activity of the left and right leg. Since we only used video encoded truth data to study infant activity, the kicking activity by the infant was discretized as a '1' if there was motion by the infant leg and a '0' if the infant leg was inactive. The overall activity by the infant represented in the fourth subgraph was obtained by a logical "OR" operation of the left and right leg. The activity graph in Figure 8 above shows that despite stimulus activation during the acquisition period in response to infant kicking activity, the stimulus was not successful in significantly increasing infant kicking activity. In fact, Figure 8, subgraphs two and three show that the infant was the most active in the first 100 s of the experimental protocol and then the activity decreased subsequently. This may be because a) the infant was tired, b) the audio stimulus was ineffective in increasing activity of the infant, or c) the infant had not formed the association between the stimulus and their motion yet. A second test following the same protocol was conducted after the infant was soothed by a parent. The activity chart for test 2 is shown in Figure 9.

Each of the subgraphs in Figure 9 represent the same information as discussed for the Figure 8 subgraphs. Once again, the stimulus was activated for positive reinforcement of infant motion however, unlike in the first test it is more difficult to deduce whether there was a subsequent increase or decrease in the infant activity. Therefore, a more detailed analysis was conducted for comparison of the baseline minute with each of the acquisition minutes studied separately. These results are discussed for the three kinematic metric of infant kicking motion in the subsequent subsections.

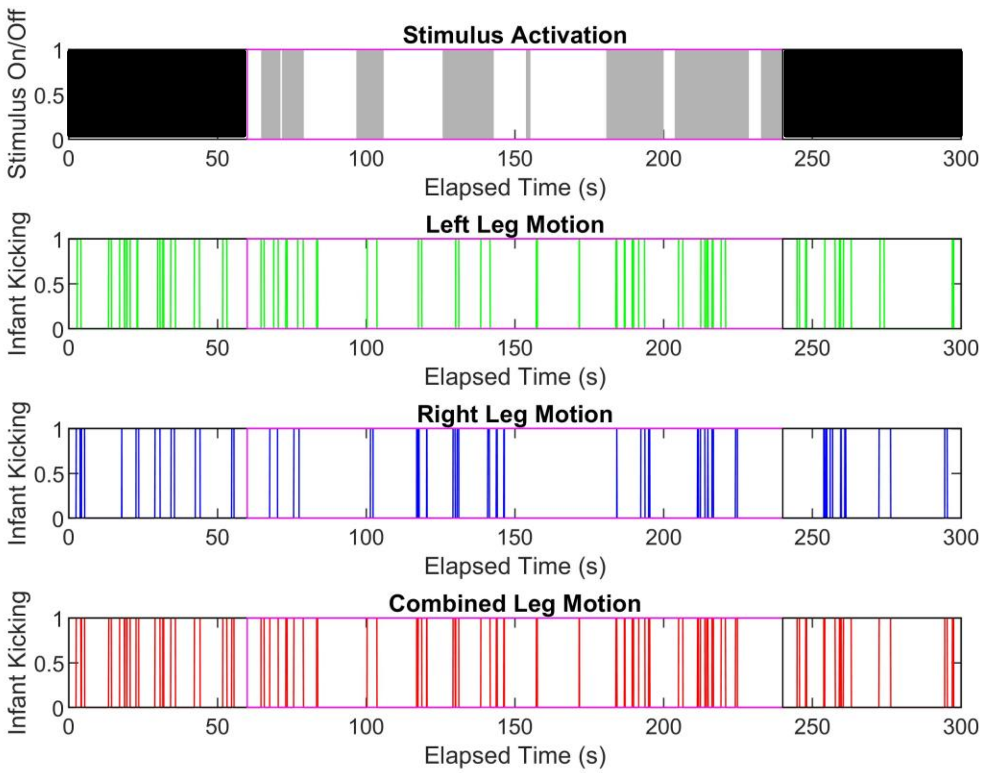


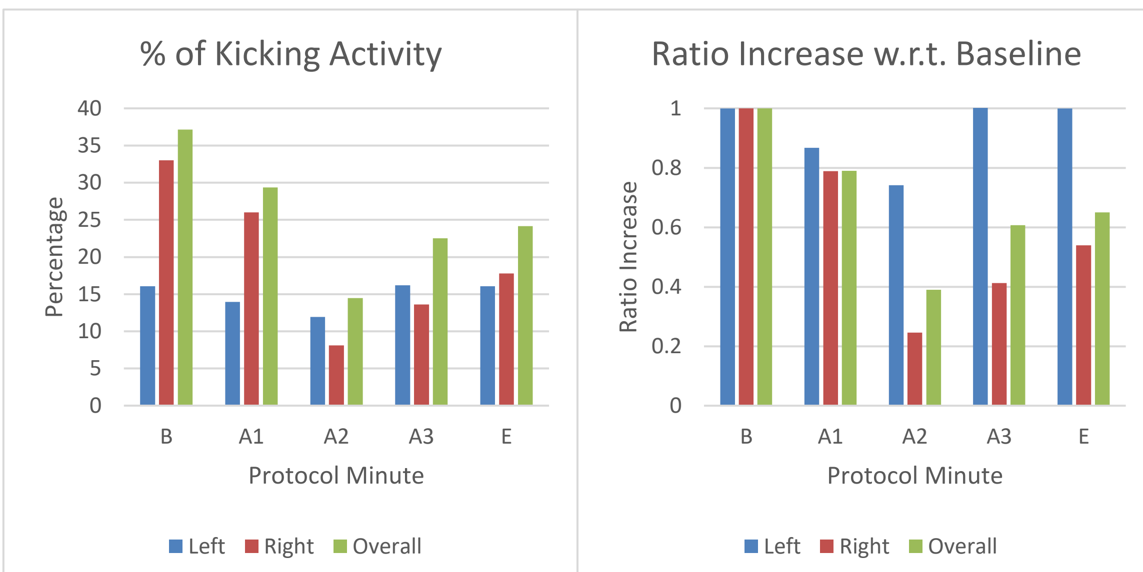
Figure 9. Audio Stimulus Activity Charts Test 2

7.1.1 Kicking Frequency

The results for the kicking frequency defined as the percentage of activity detected during each minute of test 1 and test 2 of the audio stimulus, are presented in Table 3 and Figure 10 and Table 4 and Figure 11 respectively.

Table 3. Percentage of Kicking Activity as a Function of the Number of Collected Data Samples for Audio Test 1

	% of Kicking Activity			Ratio Increase w.r.t Baseline		
	Left	**Right**	**Overall**	**Left**	**Right**	**Overall**
B	16.07	33	37.15	1	1	1
A1	13.94	26.02	29.34	0.87	0.79	0.79
A2	11.91	8.12	14.48	0.74	0.25	0.39
A3	16.18	13.61	22.54	1.01	0.41	0.61
E	16.06	17.79	24.16	1.00	0.54	0.65



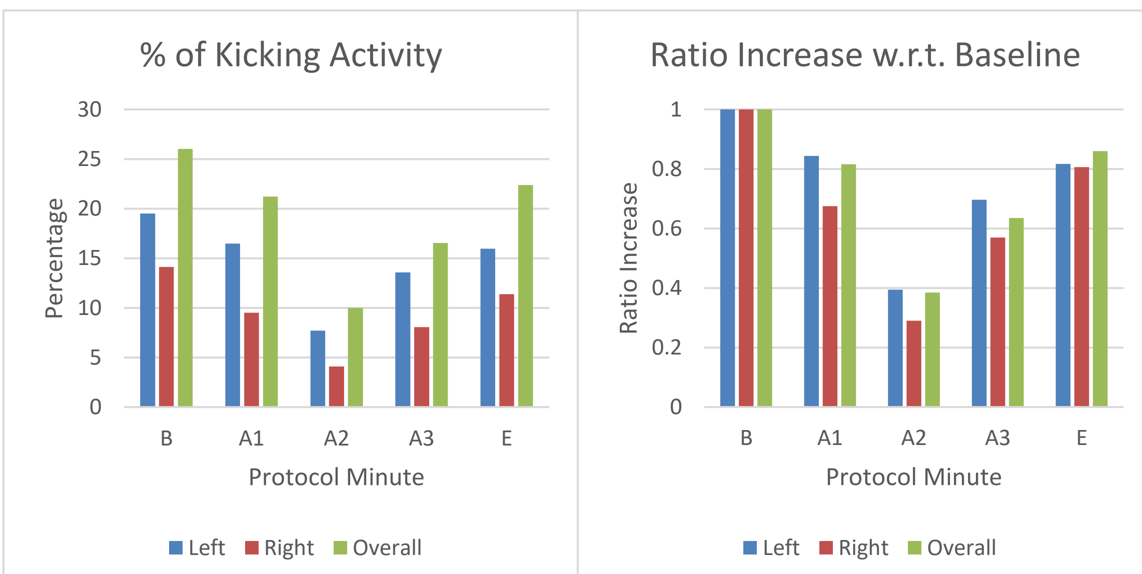
(a) (b)

Figure 10. Percentage of Activity Per Minute for Test 1 of Audio Stimulus

From test 1 results we see that there is a subsequent decrease in activity as compared with baseline in all three of the acquisition periods and the extinction period for both the right leg and the overall activity. The left leg shows an increase in the percentage of samples with activity during acquisition 3 however, as seen in figure 10b, this increase is not significant as it is below the 1.5 times increase with respect to the baseline. The test 2 results show a similar decrease in percentage of activity with respect to the baseline for all three of the acquisition periods and the extinction period.

Table 4. Percentage of Kicking Activity as a Function of the Number of Collected Data Samples for Audio Test 2

	% of Kicking Activity			Ratio Increase w.r.t Baseline		
	Left	**Right**	**Overall**	**Left**	**Right**	**Overall**
B	19.52	14.12	26.02	1	1	1
A1	16.46	9.52	21.21	0.84	0.67	0.82
A2	7.70	4.10	10.01	0.39	0.29	0.38
A3	13.59	8.05	16.53	0.70	0.57	0.64
E	15.95	11.38	22.37	0.82	0.81	0.86



(a) (b)

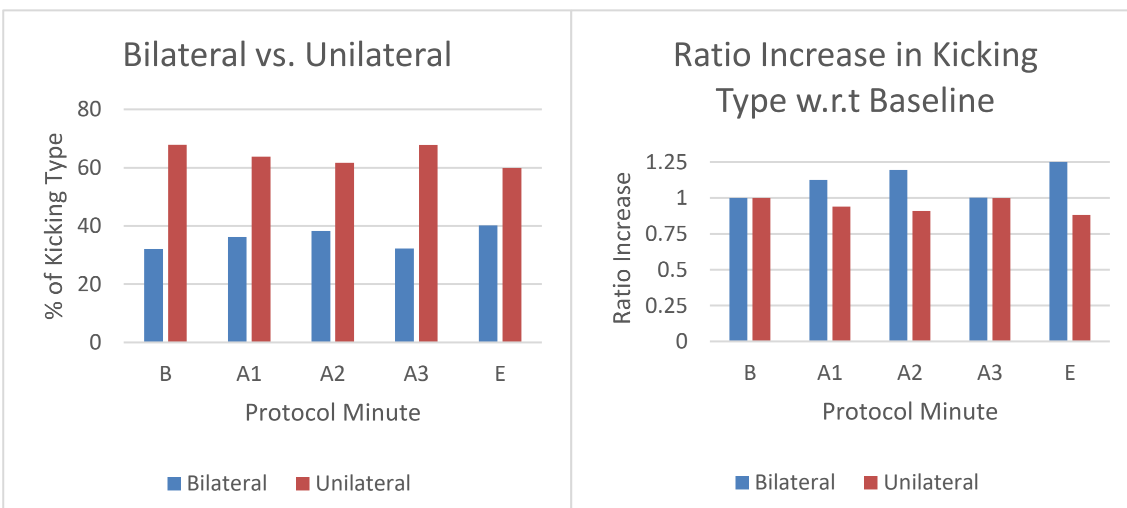
Figure 11. Percentage of Activity Per Minute for Test 2 of Audio Stimulus

7.1.2 *Frequency of Bilateral vs. Unilateral Kicking*

The second metric studied to identify an increase in infant activity as a response to introduction to the stimulus was frequency of bilateral vs. unilateral kicking measured by the increase in bilateral kicking as opposed to unilateral kicking. The results of this metric after test 1 are shown in the Table 5 below and represented in Figure 12.

Table 5. Frequency of Baseline vs. Unilateral Kicking for Audio Test 1

	% of Bilateral vs. Unilateral Kicking		Ratio Increase w.r.t baseline	
	Bilateral	**Unilateral**	**Bilateral**	**Unilateral**
B	32.09	67.91	1	1
A1	36.16	63.84	1.13	0.94
A2	38.32	61.68	1.19	0.91
A3	32.20	67.80	1.00	1.00
E	40.12	59.88	1.25	0.88



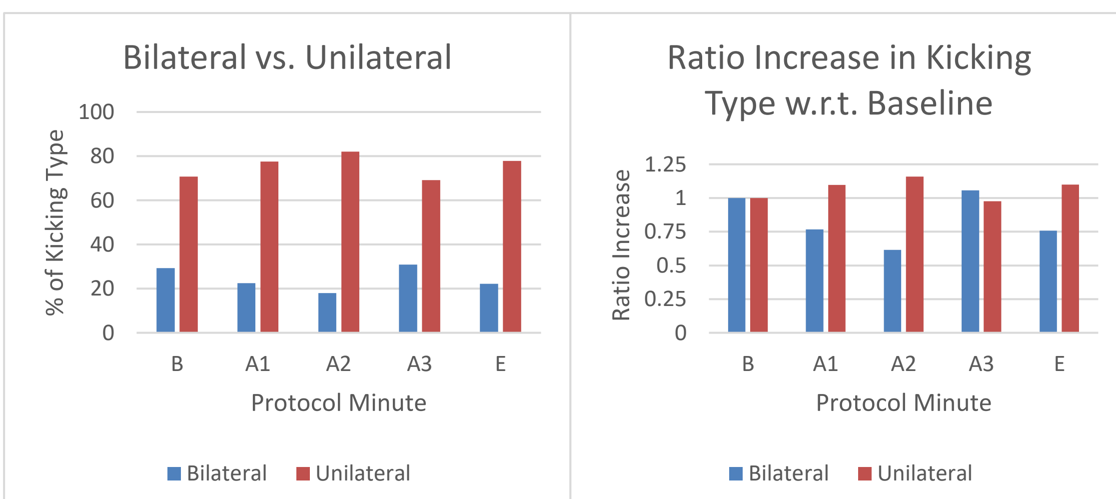
(a) (b)

Figure 12. Bilateral vs. Unilateral Kicking Test 1 of Audio Stimulus

As seen from Table 5 and Figure 12a, there was an increase in the percentage of bilateral kicking from baseline in acquisition periods one and two and extinction despite the preference shown by the infant for unilateral kicking. However, as seen in Figure 12b, the increase in bilateral kicking in acquisition periods one and two is below the metric of significant increase of 1.5 times the baseline. Therefore, despite a positive trend we cannot sufficiently conclude that the stimulus has had an effect on the bilateral kicking activity of the infant. The results for bilateral kicking activity of the infant for test 2 are shown in Table 6 and Figure 13.

Table 6. Frequency of Bilateral vs. Unilateral Kicking for Audio Test 2

	% of Bilateral vs. Unilateral Kicking		**Ratio Increase w.r.t Baseline**	
	Bilateral	**Unilateral**	**Bilateral**	**Unilateral**
B	29.28	70.72	1	1
A1	22.48	77.52	0.77	1.10
A2	18	82	0.61	1.16
A3	30.91	69.10	1.06	0.98
E	22.21	77.80	0.79	1.10



(a) (b)

Figure 13. Bilateral vs. Unilateral Kicking Test 2 of Audio Stimulus

From the test 2 results of the audio stimulus, we see that the percentage of bilateral kicking increased in acquisition three and the percentage of unilateral kicking decreased. In acquisition one and acquisition two, we notice that the percentage of unilateral kicking has increased. This increase in either bilateral or unilateral kicking however, in any of the acquisition periods, is once again not significant by our metric of 1.5 times. Therefore, no definitive conclusions can be made about the effect of the stimulus on infant activity.

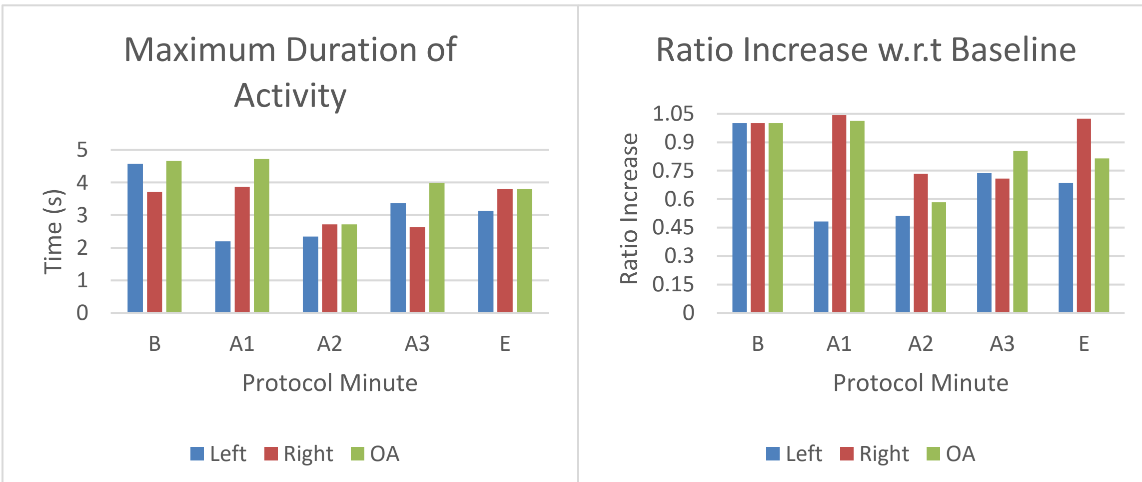
7.1.3 Duration of Continuous Activity

The third metric that was studied was the duration of continuous activity measured by the maximum and average duration of continuous activity. The results for the maximum duration of continuous activity by the infant for test 1 of audio are shown in Table 7 and Figure 14.

Table 7. Maximum Duration of Continuous Activity Measured as Time Elapsed for Audio Test 1

	Maximum Duration (seconds)			Ratio Increase w.r.t. baseline		
	Left	**Right**	**OA**	**Left**	**Right**	**OA**
B	4.57	3.71	4.66	1	1	1
A1	2.2	3.87	4.72	0.48	1.04	1.01
A2	2.34	2.72	2.7199	0.51	0.73	0.58
A3	3.37	2.63	3.98	0.74	0.71	0.85
E	3.13	3.8	3.8	0.68	1.02	0.82

From Table 7 we see that the maximum duration of continuous activity decreased for the left leg from baseline through all periods of acquisition and the extinction period. We also see that the maximum duration of continuous activity for the right leg increases in acquisition one however, decreases subsequently in acquisition 2 and 3. The maximum duration of activity once again increased for the extinction period as compared with baseline. However, as seen in figure 14b, the increase in maximum duration for right leg in acquisition 1 is below the metric of significance i.e. the increase is less than 1.5 times the baseline. When the activity of the left leg and right leg is studied collectively as an overall activity, we see that there is an increase in the maximum duration of overall activity as compared with baseline only in acquisition 1. However, once again this increase does not achieve the metric of significance.



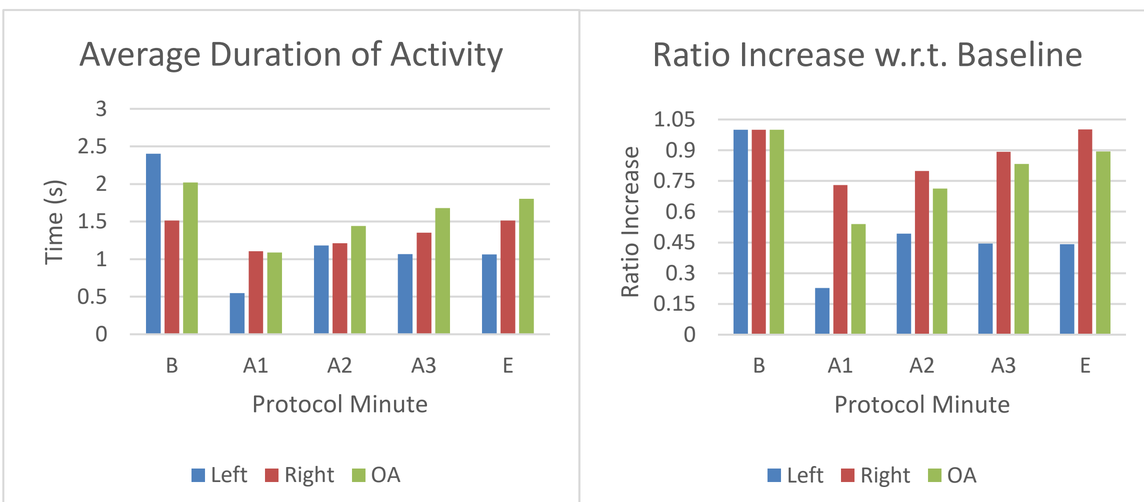
(a) (b)

Figure 14. Maximum Duration of Activity for Test 1 of Audio Stimulus

The second method through which we studied duration of motion was the average of the periods of continuous motion detected in each protocol minute. This data is represented in Table 8 and Figure 15. The average duration of motion for the left leg has also decreased in all the acquisition minutes and extinction minute with respect to the baseline. The average duration of activity for the right leg also shows no increase in infant activity for any of the acquisition periods or the extinction periods. This is reflected in the decrease in the average duration of overall activity as compared with baseline in subsequent protocol minutes from baseline. This suggests that either the association between the audio stimulus and movement was not formed by the infant or that the stimulus was ineffective in providing sufficient positive feedback to encourage increased activity.

Table 8. Average Duration of Continuous Activity Measured as Time Elapsed for Audio Test 1

Average Duration (seconds)				Ratio Increase w.r.t. baseline		
	Left	**Right**	**OA**	**Left**	**Right**	**OA**
B	2.40	1.51	2.02	1	1	1
A1	0.55	1.11	1.09	0.23	0.73	0.54
A2	1.18	1.21	1.44	0.49	0.80	0.71
A3	1.07	1.35	1.68	0.44	0.89	0.83
E	1.06	1.52	1.80	0.44	1.00	0.89



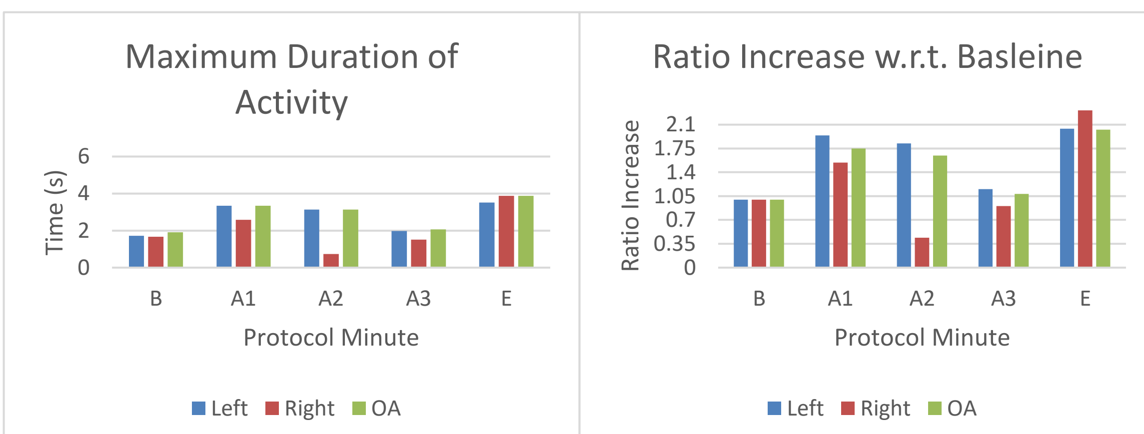
(a) (b)

Figure 15. Average Duration of Motion for Test 1 of Audio Stimulus

The test results of maximum and average duration of activity for test 2 are shown in Table 9 and Figure 16 and Table 10 and Figure 17 respectively. The results of maximum duration for all three acquisition periods show an increase in maximum duration of activity for the left leg with respect to the baseline. The right leg only shows an increase in activity for acquisition one whereas the overall activity shows an increase in maximum duration for all three of the acquisition periods. The increase in maximum duration is significant for both acquisition one and two as well as the extinction period. The increase in maximum duration is also significant by the 1.5 times metric for acquisition one of right leg. This translates into a significant increase in the overall activity in acquisition one and acquisition two of the overall activity.

Table 9. Maximum Duration of Activity Measured as Time Elapsed for Audio Test 2

Maximum Duration (seconds)				Ratio Increase w.r.t. Baseline		
	Left	**Right**	**OA**	**Left**	**Right**	**OA**
B	1.72	1.67	1.91	1	1	1
A1	3.34	2.58	3.34	1.94	1.54	1.75
A2	3.14	0.73	3.14	1.83	0.44	1.64
A3	1.98	1.51	2.07	1.15	0.90	1.08
E	3.51	3.87	3.87	2.04	2.32	2.03

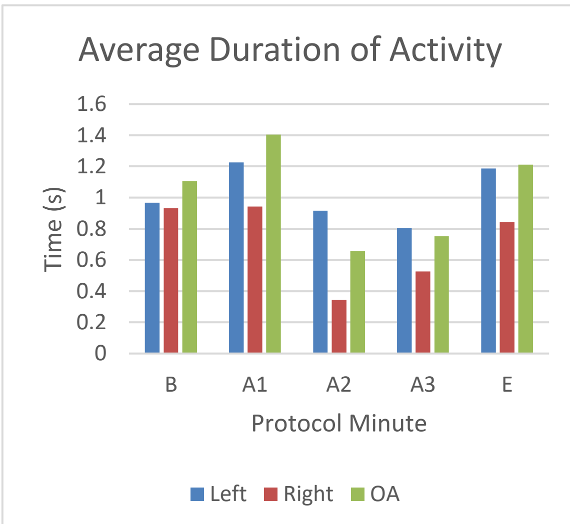


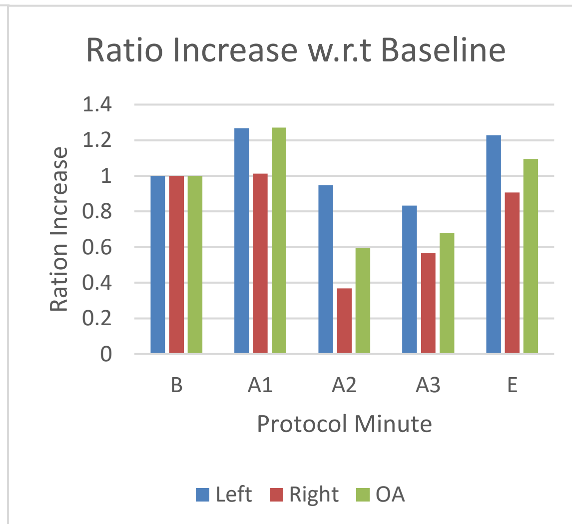
(a) (b)

Figure 16. Maximum Duration of Activity for Test 2 of Audio Stimulus

Table 10. Average Duration of Activity Measured as Time Elapsed for Audio Test 2

	Average Duration (seconds)			Ratio Increase w.r.t. baseline		
	Left	**Right**	**OA**	**Left**	**Right**	**OA**
B	0.97	0.93	1.11	1	1	1
A1	1.23	0.94	1.40	1.27	1.012	1.27
A2	0.92	0.34	0.66	0.95	0.37	0.59
A3	0.80	0.53	0.75	0.83	0.56	0.68
E	1.19	0.84	1.21	1.23	0.91	1.10





(a) (b)

Figure 17. Average Duration of Activity for Test 2 of Audio Stimulus

The average duration of continuous activity shows an increase in the acquisition one for both the left and right leg. The average duration of activity is also increased in the extinction period for the left leg. This translated into an increase in the average duration of continuous activity for acquisition one and the extinction periods however, none of these increases meet the metric of significance of 1.5 times the baseline.

From the above analysis we see that even though there is an increase in the activity of the infant on two of the three metrics used to study the infant activity, namely the percentage of bilateral kicking and the maximum and average duration of overall kicking, the metric of significance is only met for the maximum duration of kicking making a poor case for the effectiveness of the audio stimulus in encouraging an increase in activity. We additionally also observe that there is generally a decrease in activity from test 1 to test 2 suggesting that despite the break in between the two sessions the infant may be tired by test 2. We also note that the ineffectiveness of the stimulus may also be due to the experiment duration being too short for the infant to formulate the association between their movement and the stimulus, thus requiring further testing before ruling out the effectiveness of the stimulus completely.

7.2 Results from Movement Stimulus

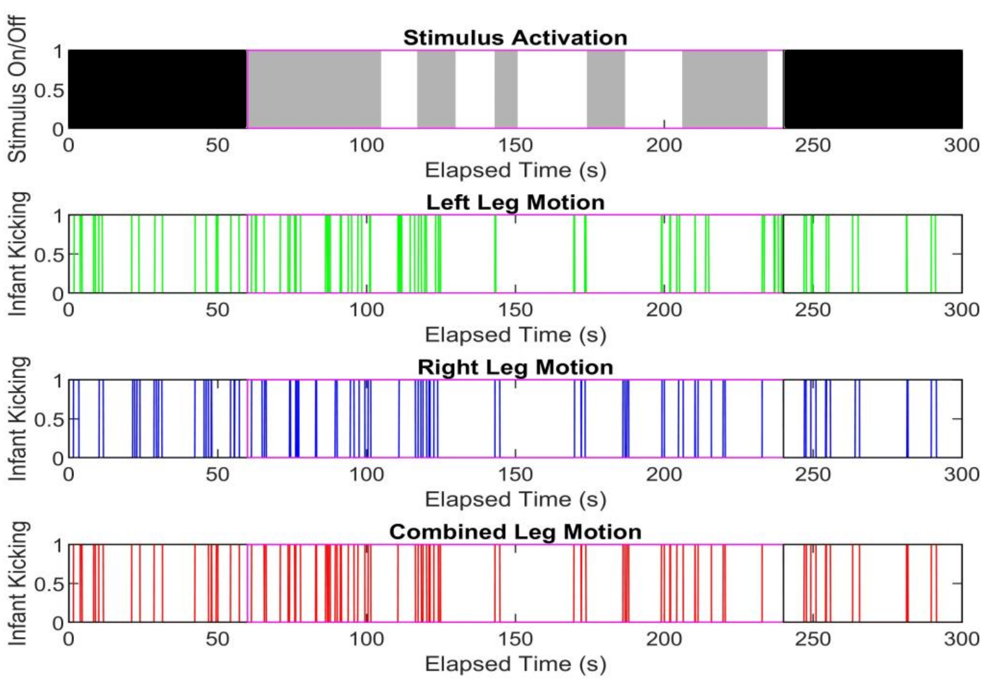


Figure 18. Activity Chart of Test 1 for Movement Stimulus

The movement stimulus was tested with a 3 months old typically developing term infant as shown in Table 2. During this experiment, once again the parent was asked to sit by the infant's head side and not interact with the infant unless the infant became fussy. The infant in this experiment did become fussy and the parent offered them a pacifier to calm them down. For the sake of consistency, the infant was allowed to keep the pacifier for the remainder of the experiment. The activity charts of the infant's activity with respect to the stimulus activation are shown in Figure 18 and Figure 19 for test 1 and test 2 respectively.

The segmentation of the above charts is the same as discussed for the audio stimulus in Section 7.1. The first minute of baseline is represented in each of the subgraphs of Figure 18 by the black box on the left, the next three minutes of acquisition with stimulus activation are represented with the pink rectangle box and the extinction minute is represented in the black box to the right. From the above chart we can see that there is certainly coordination between infant activity and the stimulus activation, however it is difficult to determine if the stimulus is able to increase the activity significantly from the baseline. In fact, the infant seems to be more active during baseline than minute two of acquisition. Therefore, any conclusive claims will depend on a deeper analysis of the infant activity. Similarly, infant activity in test 2 of the infant seems to be correlated with the activation of the stimulus as shown with continuation of kicking during stimulus activation as shown in Figure 19. However, whether this correlation has led to an increase in the infant activity needs a deeper analysis which is presented in our analysis of infant activity based on frequency of kicking, frequency of bilateral versus unilateral kicking and duration of continuous activity measured as maximum and average duration of kicking in the subsequent sections.

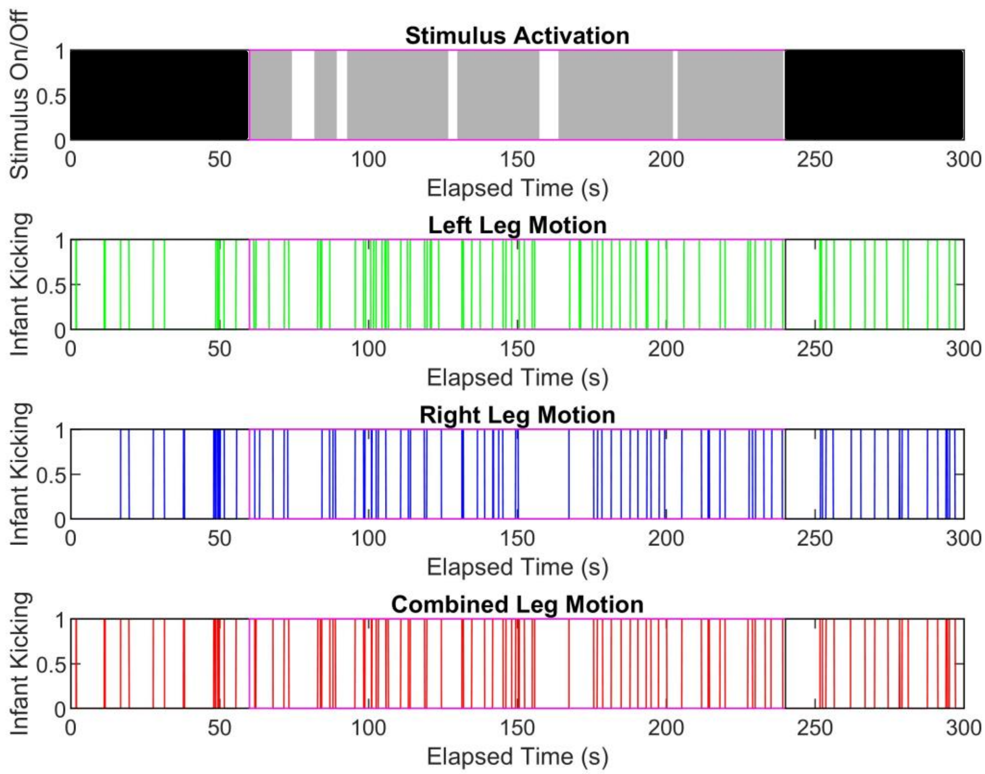


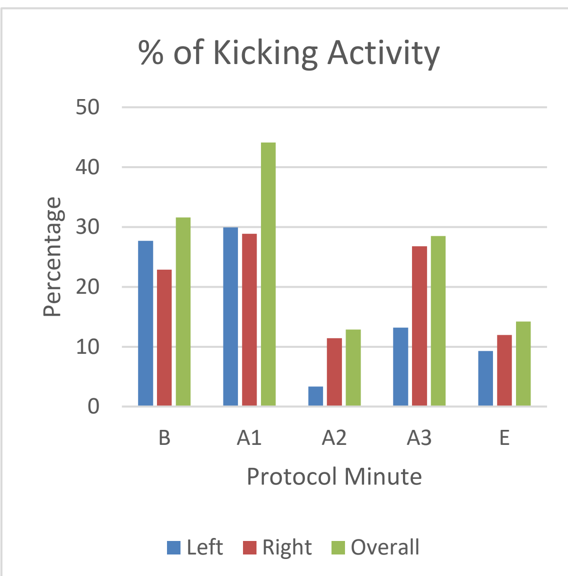
Figure 19. Activity Chart of Test 2 for Movement Stimulus

7.2.1 Kicking Frequency

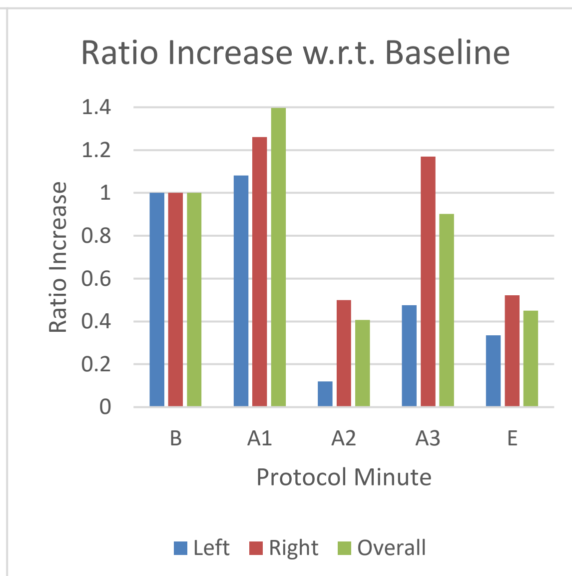
The results for the kicking frequency defined as the percentage of total activity recorded for the infant's left leg, right leg and overall activity for test 1 are represented in the Table 11 and Figure 20. Whereas, these results do show an increase in the activity of the infant for the left leg in acquisition one, there is a decrease in activity in the acquisition minutes two and three as well as the extinction minute. A similar increase in infant activity is seen in acquisition one and three of the right leg however, there is a decrease in right leg kicking activity in the acquisition 2 and extinction minutes as well. The increase in activity for acquisition one of the left and right leg is reflected in the overall activity of the infant however, there is a decrease in the infant activity for acquisition minutes two, three and the overall extinction periods.

Table 11. Percentage of Kicking Activity as a Function of the Number of Collected Data Samples for Movement Stimulus Test 1

	% of Kicking Activity			Ratio Increase w.r.t Baseline		
	Left	**Right**	**Overall**	**Left**	**Right**	**Overall**
B	27.67	22.89	31.57	1	1	1
A1	29.93	28.88	44.09	1.08	1.26	1.40
A2	3.32	11.43	12.87	0.12	0.50	0.41
A3	13.18	26.78	28.47	0.48	1.17	0.90
E	9.28	11.95	14.21	0.34	0.52	0.45



(a)



(b)

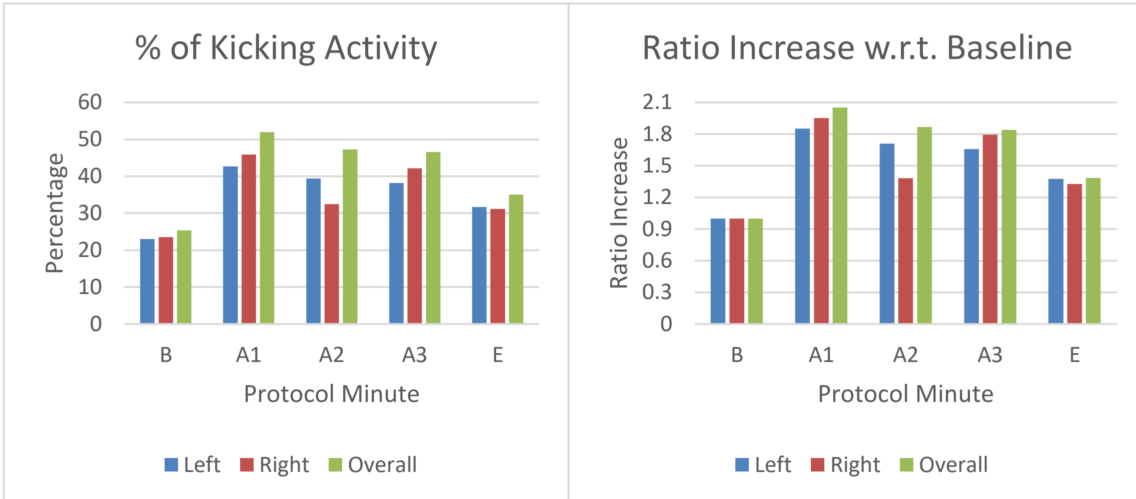
Figure 20. Percentage of Activity Per Minute for Test 1 of Movement Stimulus

As seen from Figure 20b, the increase in the kicking activity for either left leg, right leg or the overall activity does not meet the metric of significance and therefore, the correlation between the stimulus and infant activity cannot be sufficiently established.

The same analysis was done for test 2 of the movement stimulus and the results are shown in Table 12 and Figure 21. From these results we can see that the stimulus activation lead to an increase in activity in the left leg for all three acquisition periods and the extinction period. This was also observed for the activity of the right leg and translated into an increase in the overall activity of the infant for all three acquisition periods and the extinction period. As seen in Figure 21b, this increase in the activity of the left leg, right leg and the overall activity was also significant, meeting the 1.5 times increase in activity with respect to the baseline metric. This makes a positive case for the movement stimulus in increasing the activity of the infant. An increase in test 2, which was not observed in test 1 may also be due to a delayed association formed by the infant between their movement and the stimulus activation.

Table 12. Percentage of Kicking Activity as a Function of the Number of Collected Data Samples for Movement Stimulus Test 2

% of Kicking Activity				Ratio Increase w.r.t Baseline		
	Left	**Right**	**Overall**	**Left**	**Right**	**Overall**
B	23.04	23.51	25.33	1	1	1
A1	42.68	45.90	51.97	1.85	1.95	2.05
A2	39.41	32.45	47.29	1.71	1.38	1.87
A3	38.17	42.15	46.55	1.66	1.79	1.84
E	31.67	31.17	35.10	1.37	1.33	1.39



(a) (b)

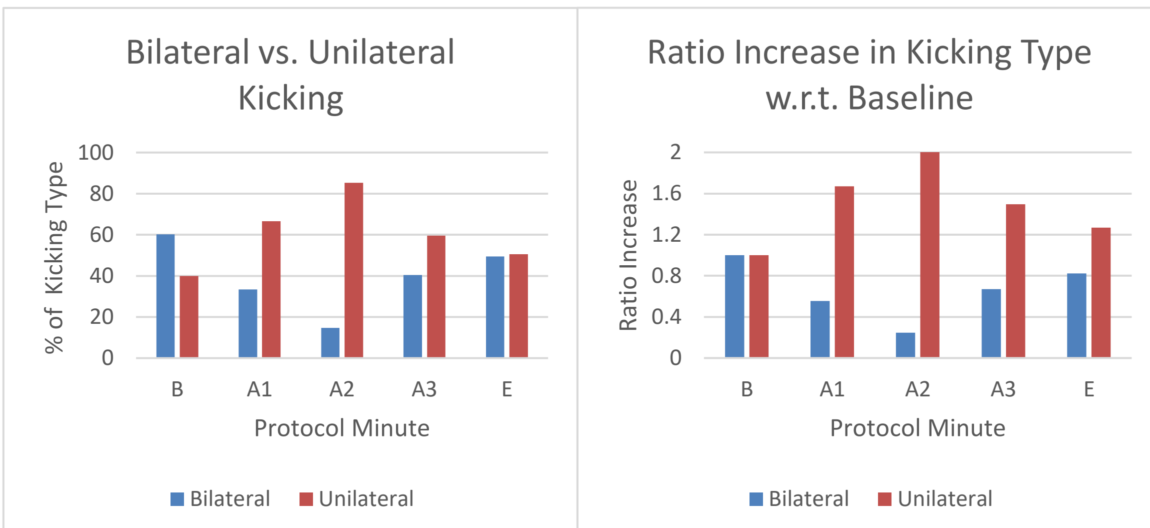
Figure 21. Percentage of Activity Per Minute for Test 2 of Movement Stimulus

7.2.2 Frequency of Bilateral vs. Unilateral Kicking

The second metric, which is a comparison of the percentage of the bilateral and unilateral kicking allows us to determine what percentage of the infant's kicking activity in each minute was bilateral or unilateral kicking. This follows from Chapter 6 where results of Jeng et.al. [35] showed that infants increased synchronous kicking with age therefore an increase in bilateral kicking is a sign of normal development. The results for test 1 of movement stimulus for bilateral vs. unilateral kicking are shown in Table 13 and Figure 22.

Table 13. Frequency of Bilateral vs. Unilateral Kicking for Movement Stimulus Test 1

% of Bilateral vs. Unilateral Kicking			Ratio Increase w.r.t Baseline	
	Bilateral	Unilateral	Bilateral	Unilateral
B	60.13	39.87	1	1
A1	33.35	66.65	0.55	1.67
A2	14.79	85.21	0.25	2.14
A3	40.38	59.62	0.67	1.50
E	49.41	50.59	0.82	1.27



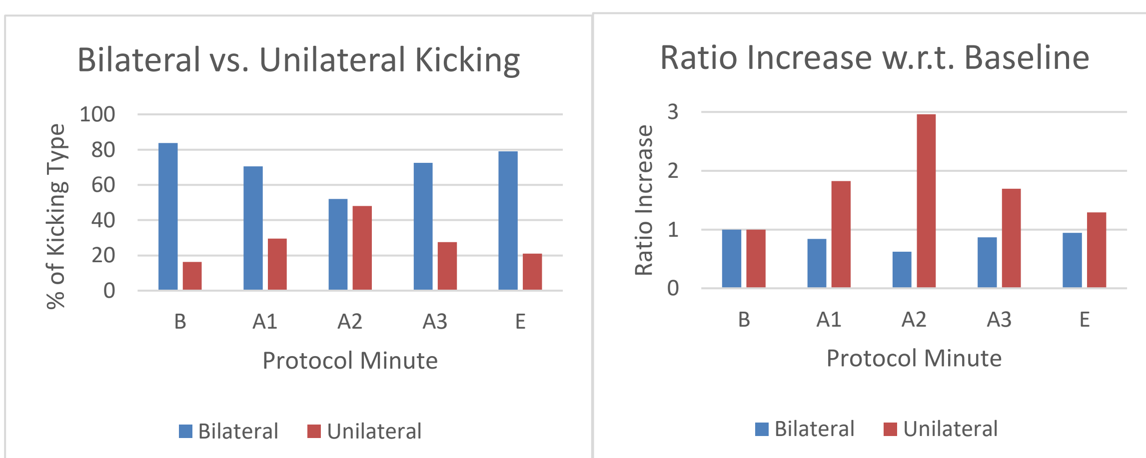
(a) (b)

Figure 22. Bilateral vs. Unilateral Kicking Test 1 of Movement Stimulus

From the results in Table 13 and Figure 22a, it can be observed that the percentage of bilateral kicking decreases in the acquisition period as compared with the baseline period. The percentage of bilateral kicking in the extinction period is still lower than the percentage of bilateral kicking in the baseline period however it is higher than the percentage of bilateral kicking in any of the acquisition period. This suggests, that the stimulus might be influencing the kicking pattern of the infant. A similar trend was also observed in test 2 of the movement stimulus the results for which are shown in Table 14 and Figure 23. There is again a decrease in the percentage of bilateral kicking in each minute of acquisition as compared with the baseline. The extinction period again shows that the bilateral kicking has decreased however, it is higher than any of the acquisition periods reinforcing that the stimulus might be influencing the kicking pattern adversely despite increasing the overall activity as seen in Section 7.1.1 though this hypothesis would require further investigation.

Table 14. Frequency of Bilateral vs. Unilateral Kicking for Movement Stimulus Test 2

% of Bilateral vs. Unilateral Kicking			Ratio Increase w.r.t Baseline	
	Bilateral	**Unilateral**	**Bilateral**	**Unilateral**
B	83.77	16.23	1	1
A1	70.43	29.57	0.84	1.82
A2	51.98	48.02	0.62	2.96
A3	72.55	27.45	0.87	1.69
E	79.05	20.95	0.94	1.29



(a) (b)

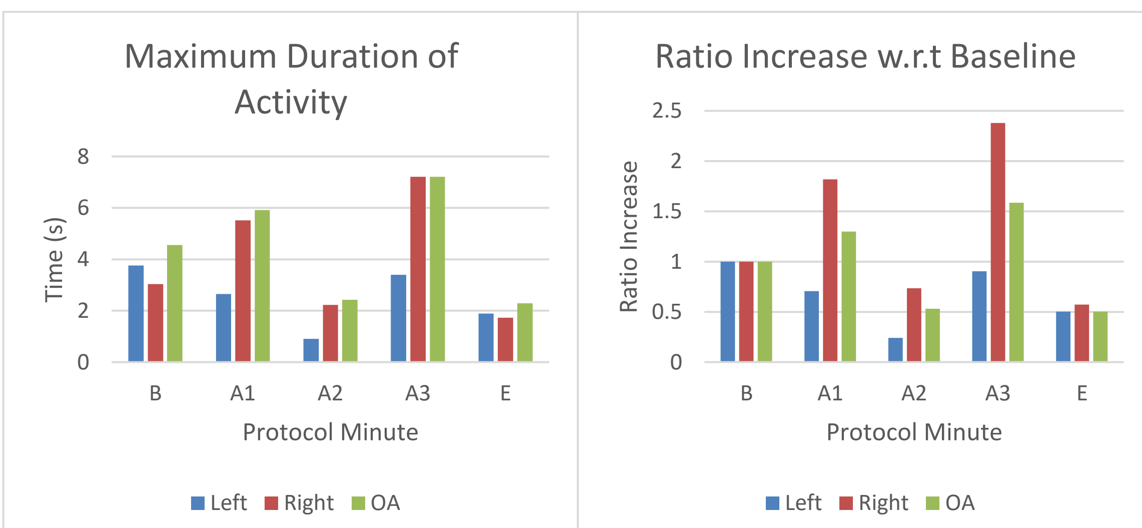
Figure 23. Bilateral vs. Unilateral Kicking Test 2 of Movement Stimulus

7.2.3 *Duration of Continuous Activity*

The third measure of increased activity was the continuous duration of motion shown by the infant. This was measured in two ways as shown in equations 8-9 through the maximum and average duration of continuous activity. The results for these two metric of duration for test 1 of movement are shown in Table 15 and Figure 24 and Table 16 and Figure 25 respectively.

Table 15. Maximum Duration of Activity Measured as Time Elapsed for Movement Stimulus Test 1

Maximum Duration (seconds)				Ratio Increase w.r.t. Baseline		
	Left	**Right**	**OA**	**Left**	**Right**	**OA**
B	3.76	3.03	4.55	1	1	1
A1	2.65	5.51	5.91	0.70	1.82	1.30
A2	0.9	2.23	2.42	0.24	0.74	0.53
A3	3.4	7.21	7.21	0.90	2.38	1.58
E	1.89	1.73	2.29	0.50	0.57	0.50

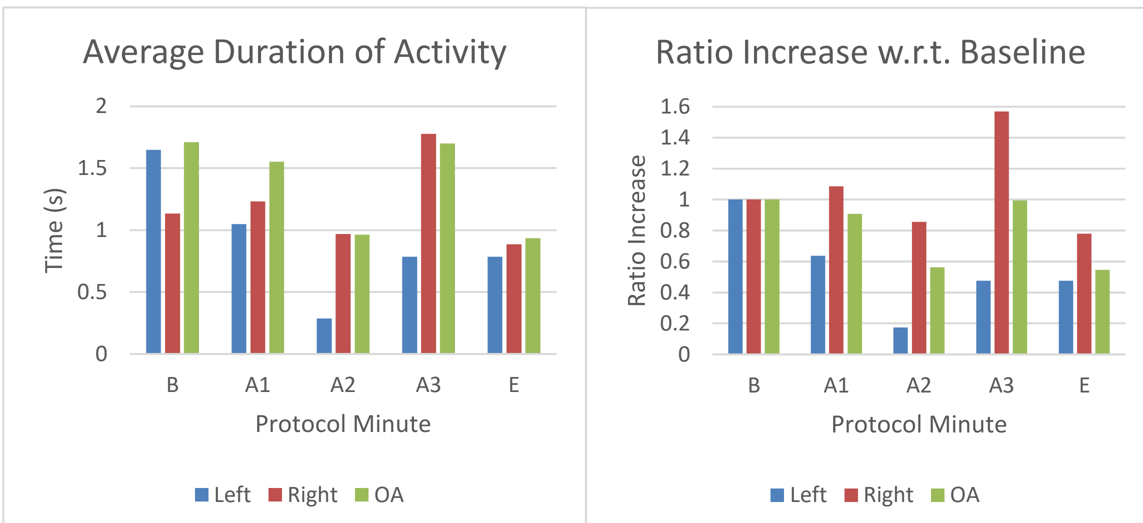


(a) (b)

Figure 24. Maximum Duration of Activity for Test 1 of Movement Stimulus

Table 16. Average Duration of Activity Measured as Time Elapsed for Movement Stimulus Test 1

	Average Duration (seconds)			Ratio Increase w.r.t. Baseline		
	Left	**Right**	**OA**	**Left**	**Right**	**OA**
B	1.65	1.13	1.71	1	1	1
A1	1.05	1.23	1.55	0.64	1.09	0.91
A2	0.29	0.97	0.96	0.17	0.86	0.56
A3	0.79	1.78	1.70	0.48	1.57	0.99
E	0.78	0.88	0.94	0.48	0.78	0.55



(a) (b)

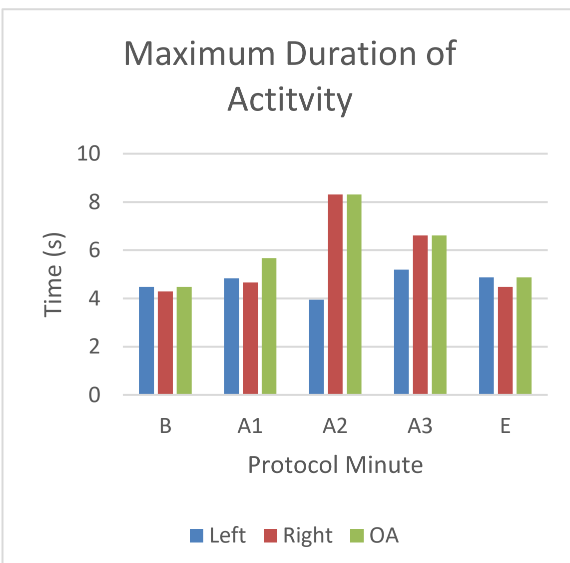
Figure 25. Average Duration of Activity for Test 1 of Movement Stimulus

From the Table 15, we can see that there is a decrease in the maximum duration of movement by the infant's left leg for all acquisition periods and the extinction period. However, there is an increase in the infant's maximum duration of continuous activity for the right leg for acquisition periods one and acquisition periods three. This increase in the maximum duration is also translated in an increase in maximum duration of overall activity for the acquisition minutes one and three. As Figure 24b shows, the increase in the infant's maximum duration of activity for acquisition periods one and three is significant as it is more than 1.5 times the baseline maximum duration of activity. However, for the overall activity, the increase in maximum duration is only significant for the acquisition three. We also notice that the increase in maximum duration with respect to the baseline is also absent for the extinction period in the activity of left leg, right leg and overall activity. The results for average duration of kicking also show no increase in the average duration of kicking activity for the left leg. There is an increase in the average duration of kicking for the right leg for the acquisition one and acquisition three. However, the increase is significant for only acquisition three. The average duration of the overall activity also shows a decrease in average duration of continuous movement with respect to the baseline in all of the experiment protocol minutes following baseline. The results for test 2 of the movement stimulus are shown in Table 17 and Figure 26 for maximum duration of activity and Table 18 and Figure 27 for average duration of activity.

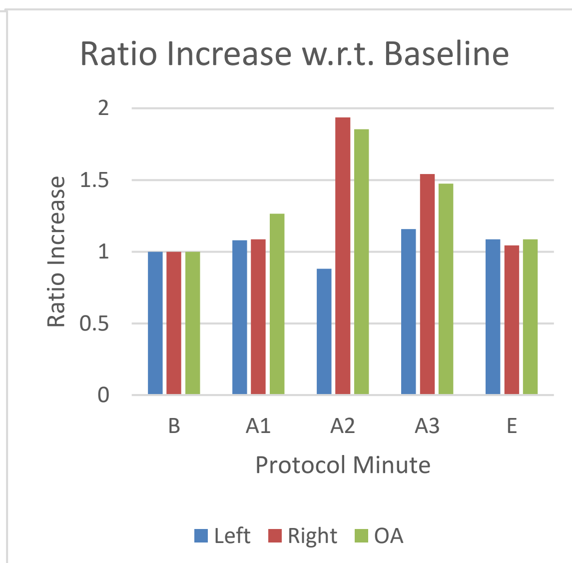
The results for the maximum duration of activity for test 2 show an influence of the movement stimulus on the duration of infant movement as seen in Table 17. An increase in maximum duration of continuous activity is observed for both the left and right legs. The left leg shows an increase in the maximum duration of continuous kicking for acquisition one, three and the extinction period. However, as seen from Figure 26b the increase is below the 1.5 times metric of significance. An increase in the maximum duration of right leg activity is observed for the infant in all three periods of acquisition and the extinction however, the increase is greater than the 1.5 times with respect to the baseline only for acquisition two and three. The overall activity of the infant likewise shows an increase in maximum duration of continuous activity for all three acquisition periods and the extinction period. However, the increase in only greater than 1.5 times the baseline for acquisition 2 of the experiment protocol.

Table 17. Maximum Duration of Activity Measured as Time Elapsed for Movement Stimulus Test 2

Maximum Duration (seconds)				Ratio Increase w.r.t. Baseline		
	Left	Right	OA	Left	Right	OA
B	4.48	4.29	4.48	1	1	1
A1	4.84	4.66	5.67	1.08	1.09	1.27
A2	3.95	8.31	8.31	0.88	1.94	1.85
A3	5.19	6.61	6.61	1.16	1.54	1.48
E	4.87	4.48	4.87	1.09	1.04	1.09



(a)



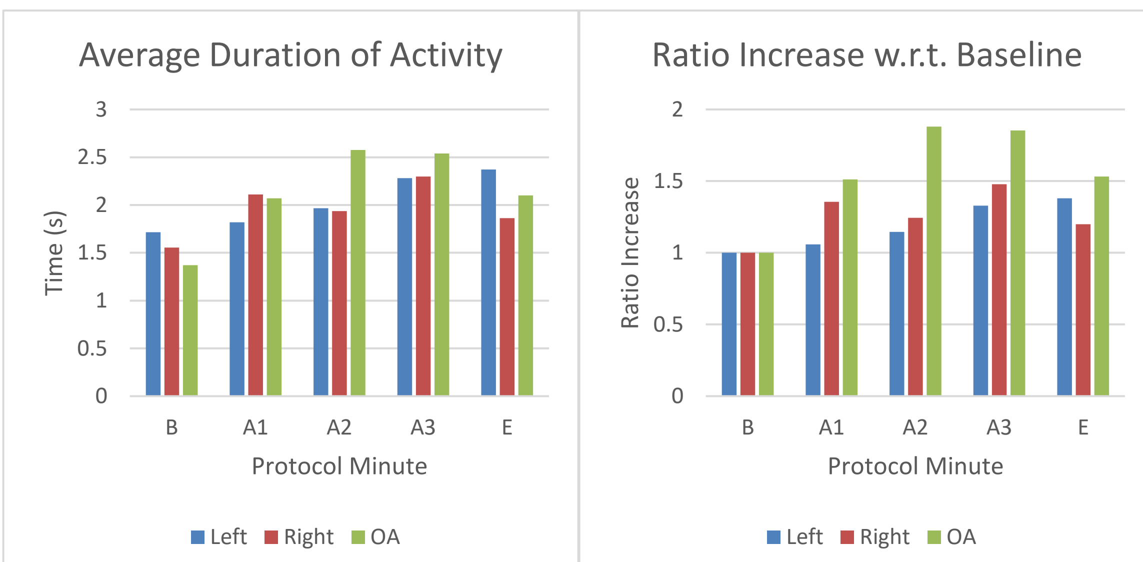
(b)

Figure 26. Maximum Duration of Activity for Test 2 of Movement Stimulus

The average duration of activity for the left leg shows an increase with respect to the baseline for all acquisition minutes and the extinction minute. This increase is also observed for the right leg and translates into an increase in the average duration of continuous activity for the overall motion of the infant as well. However, a significant increase is only observed for the overall activity of the infant in all three acquisition periods and the extinction period and not for the individual motion of the left and right leg for either the acquisition or the extinction periods as seen in Figure 27b.

Table 18. Average Duration of Activity Measured as Time Elapsed for Movement Stimulus Test 2

	Average Duration (seconds)			Ratio Increase w.r.t. baseline		
	Left	**Right**	**OA**	**Left**	**Right**	**OA**
B	1.72	1.56	1.37	1	1	1
A1	1.82	2.11	2.07	1.06	1.36	1.51
A2	1.97	1.94	2.57	1.15	1.24	1.88
A3	2.28	2.30	2.54	1.33	1.48	1.85
E	2.37	1.86	2.10	1.38	1.20	1.53



(a) (b)

Figure 27. Average Duration of Activity for Test 2 of Movement Stimulus

as compared with the baseline on two of the metrics that we studied to quantify the influence of stimuli on infant kinematics namely, the frequency of kicking and the duration of continuous activity by the infant. This increase makes a positive case for the movement of the mobile as an effective stimulus in increasing infant activity and lends support to our hypothesis that we can use stimuli as a positive reinforcement in order to encourage kicking activity among infants. This increase in infant activity and the movement stimulus was observed more significantly in test 2 of the stimulus as compared with test 1 suggesting that the correlation between the two might have been formed with time. We also observed a decrease in bilateral kicking during acquisition period than the baseline period in both tests. The percentage of bilateral kicking also rose in the extinction period. This suggested a negative association between the mobile movement and bilateral kicking. However, further investigation will be needed to investigate this as it may simply be a response of the infant to efficiently learn the minimum effort required to trigger the mobile i.e. by simply kicking with one leg. More research is required to investigate if this was a result of the infant learning the association between infant kicking and mobile movement activation if either leg kicked, or the infant's own kicking preference. We also notice that even when an increase in activity is observed in the extinction period with respect to the baseline, the increase is not significant suggesting that there may not be a carryover effect of mobile and infant activity association from the acquisition period.

7.3 Results from Visual Stimulus

The visual stimulus was tested with a three month old infant who was premature with a gestational age of 35.9 weeks whereas term infants have a gestational age of greater than or equal to 37 weeks. Therefore, the infant had an adjusted age of 2 months. The infant was laid down so that there was a direct line of sight to the mobile. The activity charts for the infant with respect to the stimulus are shown in Figure 28 and Figure 29.

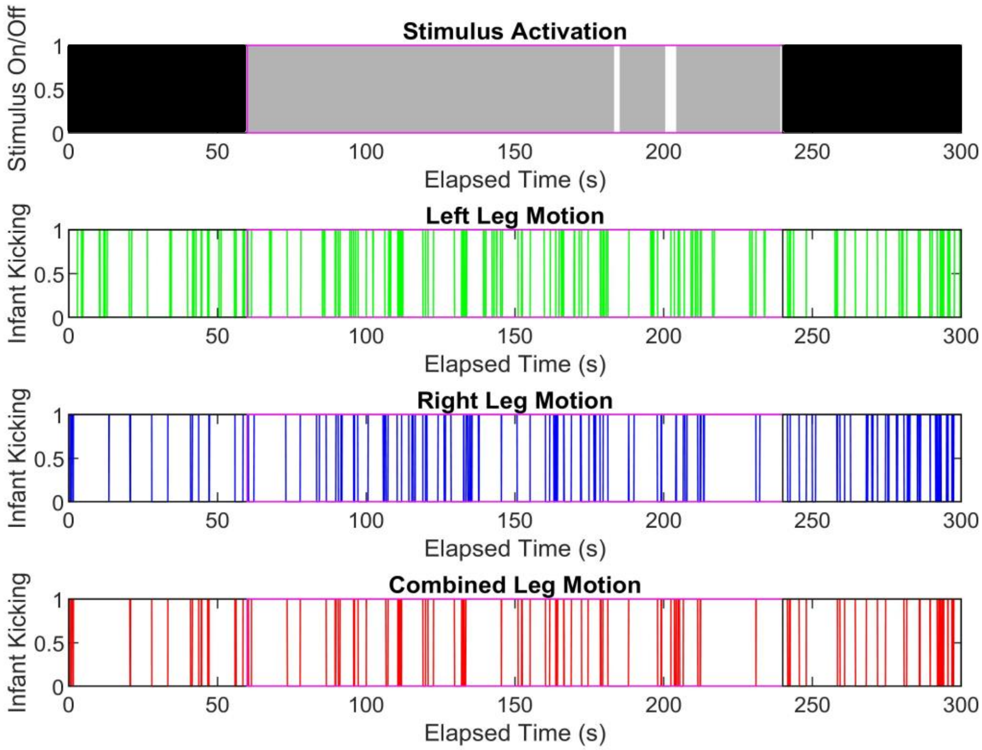


Figure 28. Activity Chart for Test 1 of Visual Stimulus

Figure 28 shows that the infant is considerably active throughout the 5 minutes of test 1 experimental protocol, therefore it is difficult to determine simply by looking at the activity charts of test 1 if there is any correlation between the infant activity and the stimulus activation during the acquisition phase of the experimental protocol. From Figure 29 we see that the infant activity during test 2 of the infant has significantly slowed down for the acquisition minutes of the experiment protocol, compared with the activity chart of test 1. This suggests that the infant may have grown tired by test 2. For the extinction period, while there is still more activity than the first 4 minutes of the test 2, it is difficult to deduce if there is reduced activity as compared with test 1 or not and requires further analysis through our study of the kinematic metrics.

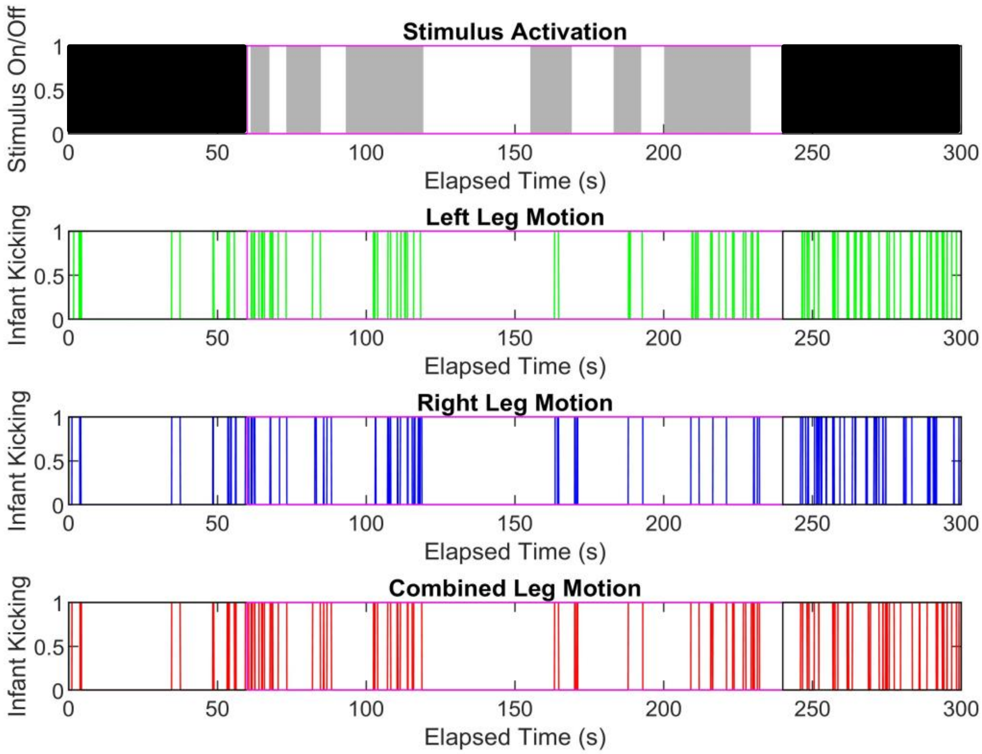


Figure 29. Activity Chart for Test 2 of Visual Stimulus

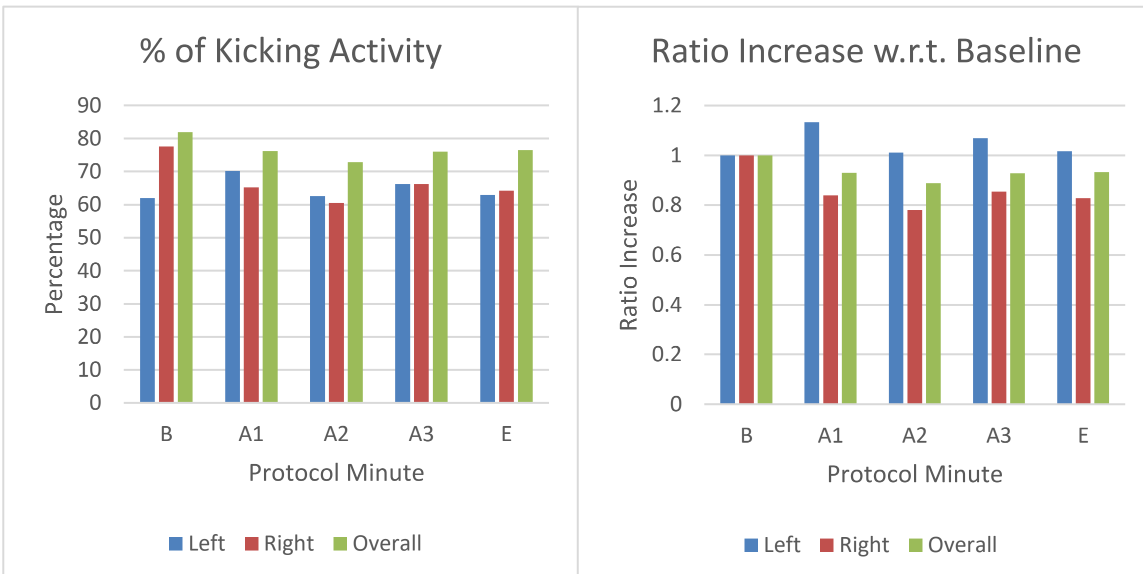
7.3.1 Kicking Frequency

Percentage of kicking activity for the infant activity for test 1 is shown in Table 19 and Figure 30. From Figure 30a and Table 19 we see that there was an increase in the infant's leg activity in all acquisition minutes as well as the extinction period. However, for neither of these minutes was the increase in activity 1.5 times the activity of baseline.

There was a decrease in the percentage of samples count per minute that detected activity for the right leg and the overall activity for all three of the acquisition minutes and for the extinction minute. This suggests that visual stimulus may not be have been an effective stimulus in encouraging infant activity. The results for the test 2 of the visual stimulus are presented in Table 20 and Figure 31. These test results however, show that there was an increase in the percentage of samples for which infant activity was detected for the left leg as compared with the baseline during the acquisition minutes one, three and the extinction period. The increase in the percentage of samples with activity was however only significant, meeting the 1.5 times criteria, during the acquisition minute one and the extinction. There was also an increase in activity based on the percentage of sample count for the right leg during acquisition minutes one and three and the extinction. The increase in the activity for right leg as compared with the baseline was greater than 1.5 times in all three cases. This increase in activity during the acquisition minutes one, three and the extinction was translated to the percentage increase of overall activity of the infant and showed an increase of more than 1.5 times in infant activity during these three intervals of the experimental protocol of test 2. This suggests that the initial ineffectiveness of the visual stimuli in increasing infant activity may have been due to a delayed association formed by the infant between their motion and the stimulus activation. We also note that despite a significant increase in infant's activity as compared with their baseline in test 2, the percentage of the time the infant is active across each minute of the two tests is significantly low. This also suggests that the infant may have grown tired by the second round of testing the experimental protocol.

Table 19. Percentage of Kicking Activity as a Function of the Number of Collected Data Samples for Visual Stimulus Test 1

	% of Kicking Activity			Ratio Increase w.r.t Baseline		
	Left	**Right**	**Overall**	**Left**	**Right**	**Overall**
B	61.97	77.61	81.97	1	1	1
A1	70.19	65.14	76.21	1.13	0.84	0.93
A2	62.62	60.58	72.80	1.01	0.78	0.89
A3	66.25	66.28	75.99	1.07	0.85	0.93
E	62.94	64.20	76.50	1.02	0.83	0.93

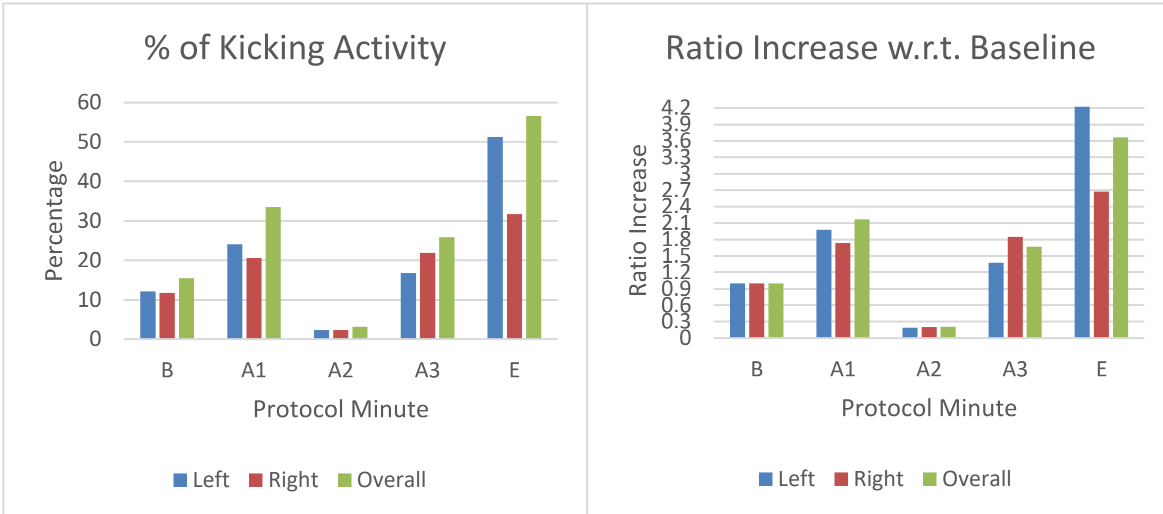


(a) (b)

Figure 30. Percentage of Activity Per Minute for Test 1 of Visual Stimulus

Table 20. Percentage of Kicking Activity as a Function of the Number of Collected Data Samples for Visual Stimulus Test 2

	% of Kicking Activity			Ratio Increase w.r.t Baseline		
	Left	**Right**	**Overall**	**Left**	**Right**	**Overall**
B	12.14	11.82	15.44	1	1	1
A1	24.06	20.57	33.44	1.98	1.74	2.17
A2	2.33	2.40	3.20	0.19	0.20	0.21
A3	16.72	21.89	25.81	1.38	1.85	1.67
E	51.25	31.65	56.56	4.22	2.68	3.66



(a) (b)

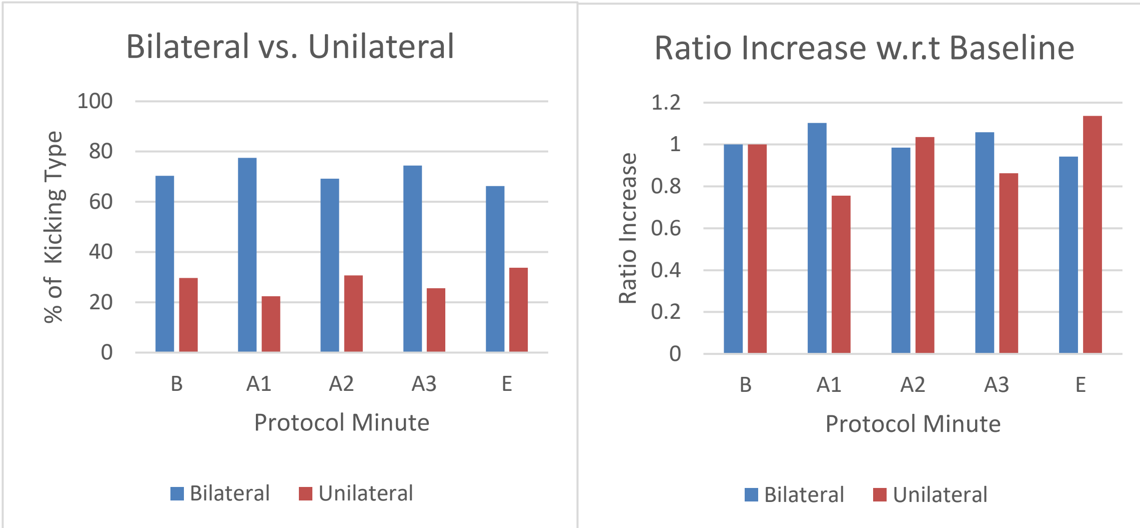
Figure 31. Percentage of Activity Per Minute for Test 2 of Visual Stimulus

7.3.2 Frequency of Bilateral vs. Unilateral Kicking

The percentage of kicking activity that was either bilateral or unilateral in each minute of the experiment protocol is shown in Table 21 and Figure 32 for test 1 and Table 22 and Figure 33 for test 2. In test 1 there was an increase in bilateral kicking in acquisition one and acquisition three however, this increase was lower than 1.5 times the baseline percentage of bilateral kicking.

Table 21. Frequency of Bilateral vs. Unilateral Kicking for Visual Stimulus Test 1

% of Bilateral vs. Unilateral Kicking			Ratio Increase w.r.t Baseline	
	Bilateral	**Unilateral**	**Bilateral**	**Unilateral**
B	70.30	29.70	1	1
A1	77.56	22.44	1.10	0.76
A2	69.26	30.74	0.99	1.04
A3	74.39	25.61	1.06	0.86
E	66.22	33.78	0.94	1.14



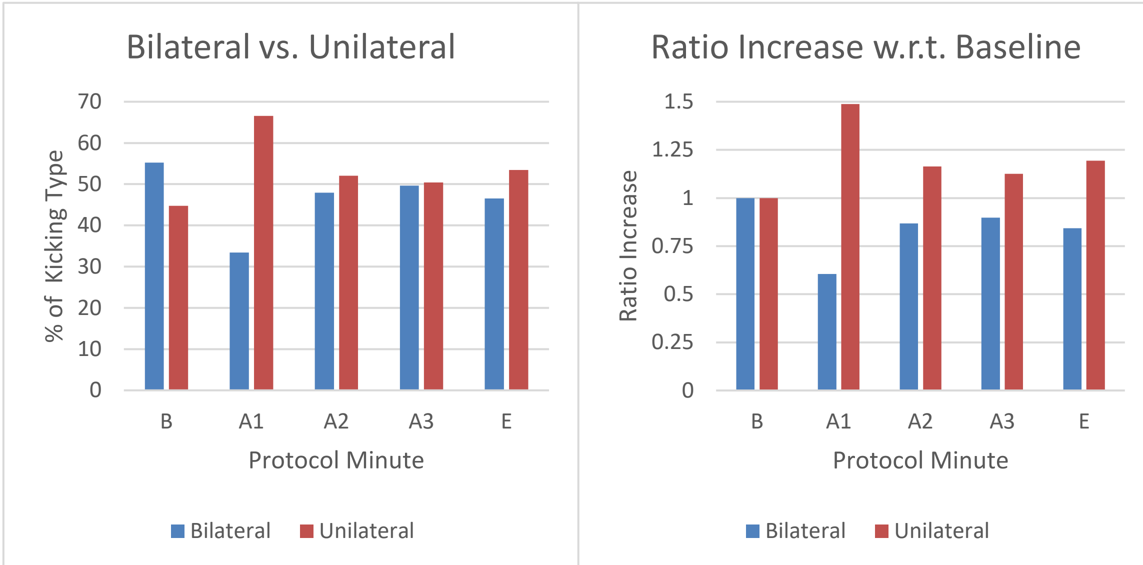
(a) (b)

Figure 32. Bilateral vs. Unilateral Kicking for Test 1 of Visual Stimulus

Test 2 results show that the percentage of bilateral kicking decreased during the acquisition and the extinction period as compared with baseline. We also note that similar to our analysis in 7.3.1 there is a decrease in the % of bilateral kicking per minute in test 2 as compared with test 1 throughout the experiment protocol further suggesting that the infant may be tired.

Table 22. Frequency of Bilateral vs. Unilateral Kicking for Visual Stimulus Test 2

	% of Bilateral vs. Unilateral Kicking		Ratio Increase w.r.t Baseline	
	Bilateral	**Unilateral**	**Bilateral**	**Unilateral**
B	55.24	44.76	1	1
A1	33.43	66.57	0.61	1.49
A2	47.92	52.08	0.87	1.16
A3	49.61	50.39	0.90	1.13
E	46.58	53.42	0.84	1.19



(a) (b)

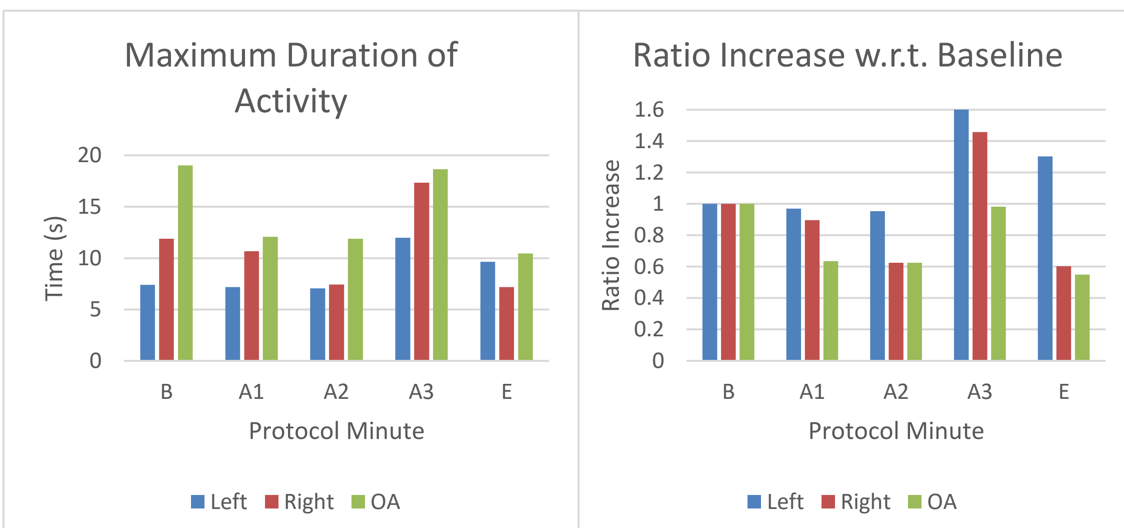
Figure 33. Bilateral vs. Unilateral Kicking for Test 2 of Visual Stimulus

7.3.3 Duration of Continuous Activity

The analysis of continuous activity of the infant for test 1 is shown in Table 23 and Figure 34 for maximum duration and Table 24 and Figure 35 for average duration. From Table 23 it can be seen that there is an increase in the maximum continuous duration of kicking for the infant for acquisition three and the extinction for left leg and for acquisition three for the right leg. However, the increase is greater than 1.5 times the baseline only for acquisition 3 of the left leg and this metric is not met for the right leg for any of the acquisition periods. When the overall activity of the legs is considered, then we see from Figure 34a that there is a decrease in the maximum duration of continuous activity for all acquisition periods and the extinction period. From Table 24 and Figure 35a we see that there is an increase in the average duration of continuous activity for the left leg for acquisition one and three as well as the extinction periods. However, the increase was not greater than 1.5 times the baseline for any of these periods. The average duration of continuous activity decreased for all acquisition periods and the extinction period for the right leg. The overall activity showed an increase in the average duration of continuous activity for acquisition three however the increase was less than 1.5 times the baseline and therefore not significant.

Table 23. Maximum Duration of Continuous Activity Measured as Time Elapsed for Visual Stimulus Test 1

	Maximum Duration (seconds)			Ratio Increase w.r.t. baseline		
	Left	**Right**	**OA**	**Left**	**Right**	**OA**
B	7.41	11.90	19.01	1	1	1
A1	7.19	10.66	12.07	0.97	0.90	0.63
A2	7.06	7.44	11.89	0.95	0.63	0.63
A3	11.97	17.35	18.66	1.62	1.46	0.98
E	9.65	7.18	10.45	1.30	0.60	0.55



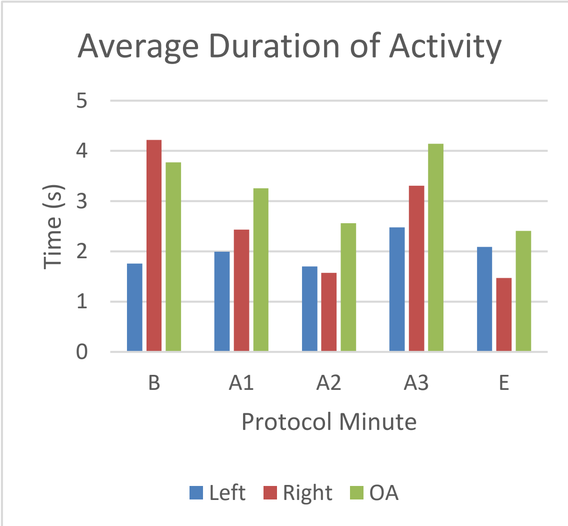
(a) (b)

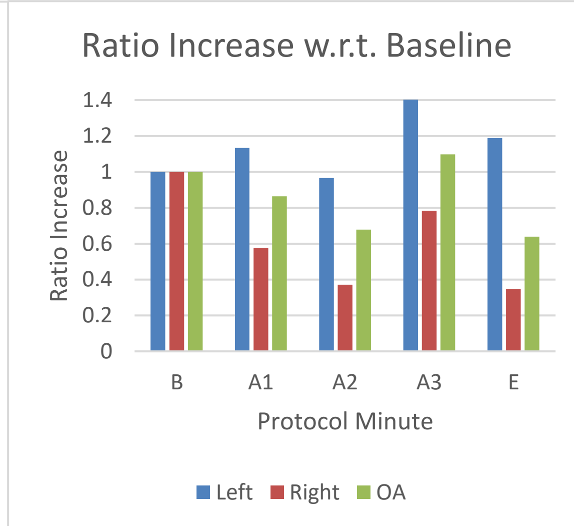
Figure 34. Maximum Duration of Activity for Test 1 of Visual Stimulus

Table 24. Average Duration of Continuous Activity Measured as Time Elapsed for Visual Stimulus Test 1

Average Duration (seconds)				Ratio Increase w.r.t. baseline		
	Left	**Right**	**OA**	**Left**	**Right**	**OA**
B	1.76	4.22	3.77	1	1	1
A1	1.99	2.43	3.26	1.13	0.58	0.86
A2	1.70	1.57	2.56	0.97	0.37	0.68
A3	2.48	3.31	4.14	1.41	0.78	1.10
E	2.09	1.47	2.41	1.19	0.35	0.64

Results from test 2 are presented in Table 25 and Figure 36 for maximum duration and Table 26 and Figure 37 for average duration of continuous activity. From Table 25 we see that the left leg shows an increase in the maximum duration of continuous activity for acquisition three and the extinction periods. However, the increase in acquisition three is less than 1.5 times the baseline maximum duration of kicking for acquisition three and therefore does not represent a significant increase. The right leg shows an increase in maximum duration of activity for the acquisition three and extinction periods and the increase in the acquisition period is 1.5 times the baseline maximum duration and is therefore considered to be significant. The overall activity of the infant also shows an increase in acquisition three and the extinction period. In both cases, the increase is greater than 1.5 times the baseline maximum duration of activity as shown in Figure 36b.





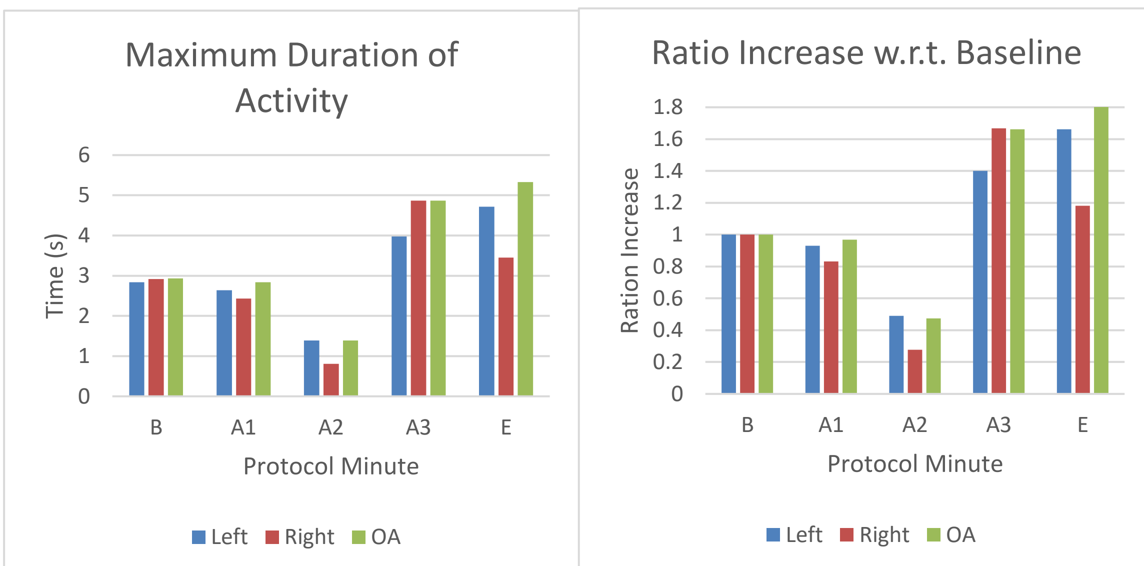
(a) (b)

Figure 35. Average Duration of Activity for Test 1 of Visual Stimulus

Table 26 shows that there was a decrease in the average duration of continuous kicking for all acquisition periods for the left leg and an increase in the average duration with respect to the baseline during the extinction period. However this increase was of less than 1.5 times the baseline average duration of kicking. The average duration of continuous kicking for the right leg increased for acquisition three and was 3.12 times the baseline average duration of kicking. The overall activity of the left and right leg showed an increase in the average duration of continuous kicking in acquisition one, three and the extinction periods however, this increase was only greater than 1.5 times the baseline for acquisition three where it was 1.68 times the baseline. Therefore, there is evidence that the visual stimulus may be effective in increasing the infant activity. We also note that similar to our analysis in 7.3.1 and 7.3.2, there is a decrease in the maximum and average durations per minute in test 2 as compared with test 1 throughout the experiment protocol further suggesting that the infant may have grown tired.

Table 25. Maximum Duration of Continuous Activity Measured as Time Elapsed for Visual Stimulus Test 2

Maximum Duration (seconds)				Ratio Increase w.r.t. baseline		
	Left	**Right**	**OA**	**Left**	**Right**	**OA**
B	2.84	2.92	2.93	1	1	1
A1	2.64	2.43	2.84	0.93	0.83	0.97
A2	1.39	0.81	1.39	0.49	0.28	0.47
A3	3.98	4.87	4.87	1.40	1.67	1.66
E	4.72	3.45	5.33	1.66	1.18	1.82

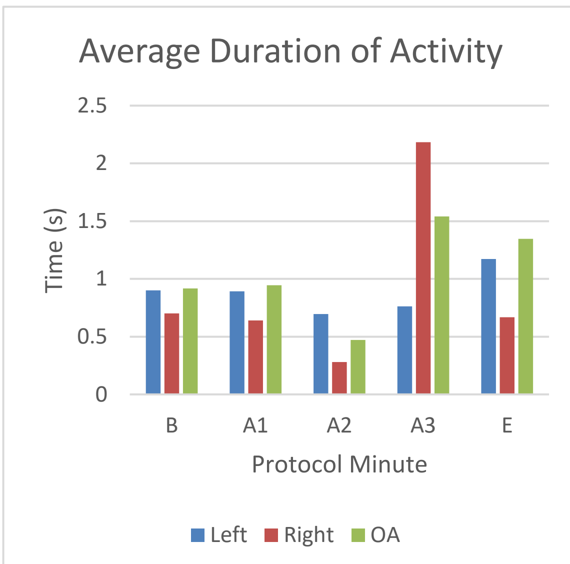


(a) (b)

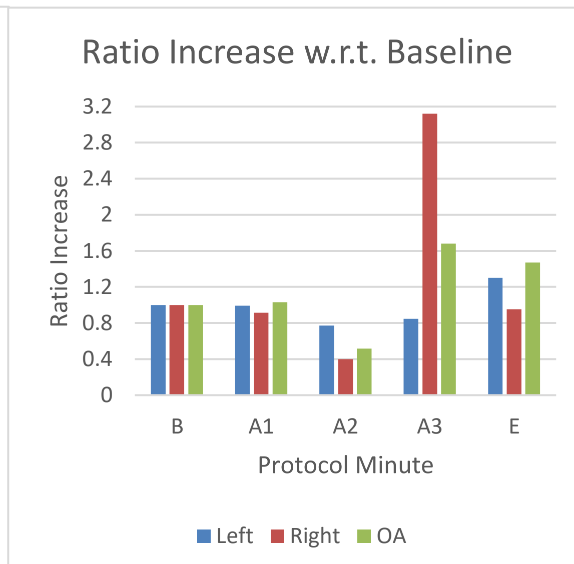
Figure 36. Maximum Duration of Activity for Test 2 of Visual Stimulus

Table 26. Average Duration of Continuous Activity Measured as Time Elapsed for Visual Stimulus Test 2

Average Duration (seconds)				Ratio Increase w.r.t. baseline		
	Left	Right	OA	Left	Right	OA
B	0.90	0.70	0.92	1	1	1
A1	0.89	0.64	0.95	0.99	0.92	1.03
A2	0.70	0.28	0.47	0.77	0.40	0.52
A3	0.76	2.18	1.54	0.85	3.12	1.68
E	1.17	0.67	1.35	1.30	0.95	1.47



(a)



(b)

Figure 37.Average Duration of Activity for Test 2 of Visual Stimulus

From the above analysis of the results, we note that the visual stimulus was able to increase the overall activity of the infant significantly on two of the three metrics we studied to quantify infant activity in response to the stimulus. A significant increase was observed for either the left leg, right leg or the overall activity of the infant in at least one of the acquisition periods for the visual stimulus for both the frequency of kicking activity per minute and the duration of continuous activity measured by the maximum and average durations of activity. The results for the visual stimulus therefore, also provide positive evidence in favour of the our hypothesis and the effectiveness of stimuli in encouraging infant activity and modifying infant behaviour.

CHAPTER 7. DISCUSSION

In the pilot study for this thesis, we verified the influence of three stimulus: audio: music, visual: light and movement to test our hypothesis that we can use these stimuli to influence the kicking activity and behaviour of infants. This could be a crucial step in improving early diagnosis of neuromuscular disorders such as cerebral palsy. We designed our system to capitalize on the stimuli typically found in the natural environment of the infant. The intent was to use positive feedback to encourage infant activity. This would further facilitate long term testing and data collection at the infant's home making early diagnosis more feasible. Our system design consisted of these stimuli integrated into an infant's mobile and triggered by an android app based on infant kicking and movement.

Our experimental protocol consisted of visiting each infant at their home and conducting two tests of five minutes in length. Each test consisted of a five minute protocol involving a baseline period (one minute), acquisition period (three minutes) and extinction period (one minute). The stimulus was only introduced during the acquisition period in response to the infant kicking such that the stimulus was activated when the infant exhibited activity by movement of either leg and only turned off following a five second period of no activity. We hypothesized that this would allow time for the infant to associate their leg motion with stimulus activation. In between test 1 and test 2, the infant's guardian was allowed to sooth them though any intervention during the actual test protocol was only allowed if the infant appeared distressed or fussy.

We analyzed the results obtained from the above experiment protocol by utilizing three kinematics of infant kicking namely: the percentage of kicking activity, the percentage of bilateral kicking versus unilateral kicking and the duration of continuous activity . These kinematic variables were selected based on previous studies that showed them to be viable characteristics of infant motion. For the analysis of these variables, we divided the acquisition period of three minutes into three subperiods of one minute each and compared the values of these variables in each of the sub acquisition periods with respect to the baseline. An increase in these variables was considered significant if it was 1.5 times that of the baseline. The results based on these stimuli are summarised in Table 28 for percentage of kicking activity. The key for Table 28 is shown in Table 27. From the Table 28 we see that all three stimulus were ineffective in the first test, test 1, in significantly increasing the percentage of kicking activity during any of the acquisition minutes. However, the movement stimulus did significantly increase the percentage of activity during test 2 with respect to the baseline, providing evidence that the infant was able to successfully form association between their leg motion and the mobile movement. Similarly, the visual stimulus was able to significantly increase infant activity with respect to the baseline in two of the acquisition periods. This also gives evidence in favour of using visual stimulus to increase infant activity. The delay in observing an increase in activity in test 2 and not in test 1 suggests that the infants may need either a longer acquisition period to form the association or some pre conditioning with the stimulus to guide them in forming the association faster. Test results from the audio stimulus also showed a decrease in activity by the infant between test 1 and test 2 which suggests that some infants may get tired between two subsequent tests and therefore may need a longer rest period. This may become important if longer testing periods are required to allow for stimulus-to-infant motion association.

Table 27. Key for Summary of Infant Kinematics and Stimulus Response

Color	Increase	Symbol	Description	Symbol	Description
	>1.5	L	Left Leg	A1	Acquisition 1
		R	Right Leg	A2	Acquisition 2
	<1.5	OA	Overall Activity	A3	Acquisition 3

Table 28. Summary of Kinematic Parameter One: Percentage of Kicking Activity

% of Kicking Activity												
	Audio				Movement				Visual			
Test 1	A1	L	R	OA	A1	L	R	OA	A1	L	R	OA
	A2	L	R	OA	A2	L	R	OA	A2	L	R	OA
	A3	L	R	OA	A3	L	R	OA	A3	L	R	OA
Test 2	A1	L	R	OA	A1	L	R	OA	A1	L	R	OA
	A2	L	R	OA	A2	L	R	OA	A2	L	R	OA
	A3	L	R	OA	A3	L	R	OA	A3	L	R	OA

The summary results for percentage of bilateral and the percentage of unilateral kicking for each stimulus are presented in Table 29 below. Table 29 follows the key presented in Table 27. This metric of kinematic analysis presents an interesting result in that all three stimuli did not seem to be effective in increasing the percentage of bilateral kicking as seen in Table 29. This could be explained through the design of the experimental protocol. In the experiment protocol, positive feedback to the infant was provided every time they kicked irrespective of whether the kicking was unilateral or bilateral. Therefore, even though two of the stimuli: movement and visual, were able to increase infant kicking activity, the positive feedback was not explicitly associated with bilateral kicking. Therefore, either infants were unable to make any association between bilateral kicking and stimulus feedback or more likely were able to find the most efficient way of triggering the stimulus. The latter explanation is more plausible since research by Csibra in [3] and Sargent et al. in [14], as discussed in chapter 2, suggests that infants tend to associate a principle of efficiency with a goal oriented task. In our experiment, the goal for the infant is to trigger the stimulus and if the triggering can be accomplished with unilateral kicking then the infant may be encouraged to kick unilaterally instead. This could explain why we saw a negative association between the movement stimulus and bilateral kicking in chapter seven, section 7.2.2. This could be verified in subsequent testing by modifying the experimental protocol such that the positive feedback from the stimulus is provided only during bilateral kicking.

Table 29. Summary of Kinematic Parameter Two: Percentage of Bilateral vs. Unilateral Kicking

% of Bilateral vs. Unilateral Kicking			
	Audio	Movement	Visual
Test 1	A1	A1	A1
	A2	A2	A2
	A3	A3	A3
Test 2	A1	A1	A1
	A2	A2	A2
	A3	A3	A3

The third kinematic variable was continuous duration of activity. This was studied as maximum duration of continuous activity and average duration of continuous activity. The results for maximum duration of continuous activity are shown in Table 30. From Table 30, we once again see that there may be a correlation between the movement and infant's activity since an increase of greater than 1.5 times of maximum duration of continuous kicking was observed for the right leg and overall activity in the acquisition minute three of test 1 and acquisition minute two of test two and an increase of more than 1.5 times for the right leg in acquisition one of test 1 and acquisition minute two of test 2. Similarly, there was an increase for the visual stimulus in the maximum duration of continuous activity in acquisition two of test 1 and acquisition three of test 2. However, on this kinematic variable, the audio stimulus also showed an increase in the maximum duration of continuous kicking during acquisition one and two of test two. However, as seen in Table 31, which summarizes the average duration of continuous kicking activity, the audio stimulus once again does not lead to an increase of 1.5 times the baseline average kicking duration and hence the increase in maximum duration is not sufficient to claim that the audio stimulus was successful in increasing infant activity. Table 31 also shows an increase in infant activity in terms of average duration of activity for the movement stimulus in acquisition minutes one and three of test one and acquisition two and three of test 2. Visual stimulus shows an increase in average duration of infant activity in acquisition three of test 1 and test 2. Based on these mixed results, there is some evidence that all these stimuli have some effect on continuous duration, but no firm conclusions can be made until there are further pilot studies.

In summary, this pilot study provides some evidence that the movement and visual stimuli can be successfully used to increase infant activity and therefore, provides evidence in favour of our hypothesis that the introduction of stimuli in a goal based task that also provides positive feedback can be used to modify infant behaviour and increase infant activity. We also observe, that infants tended to get tired during two sessions despite a short break between the two. However, whether this adversely affected the results requires further investigation. The results also show that there may be a need to modify the experimental protocol to study the effect of the stimuli on certain kinematic variables such as the percentage of bilateral versus the percentage of unilateral kicking.

Table 30. Summary of Kinematic Parameter Three: Maximum Duration

Maximum Duration												
	Audio				Movement				Visual			
Test 1	A1	L	R	OA	A1	L	R	OA	A1	L	R	OA
	A2	L	R	OA	A2	L	R	OA	A2	L	R	OA
	A3	L	R	OA	A3	L	R	OA	A3	L	R	OA
Test 2	A1	L	R	OA	A1	L	R	OA	A1	L	R	OA
	A2	L	R	OA	A2	L	R	OA	A2	L	R	OA
	A3	L	R	OA	A3	L	R	OA	A3	L	R	OA

Table 31. Summary of Kinematic Parameter Three: Average Duration

Average Duration												
	Audio				Movement				Visual			
Test 1	A1	L	R	OA	A1	L	R	OA	A1	L	R	OA
	A2	L	R	OA	A2	L	R	OA	A2	L	R	OA
	A3	L	R	OA	A3	L	R	OA	A3	L	R	OA
Test 2	A1	L	R	OA	A1	L	R	OA	A1	L	R	OA
	A2	L	R	OA	A2	L	R	OA	A2	L	R	OA
	A3	L	R	OA	A3	L	R	OA	A3	L	R	OA

Although, we can conclude positive evidence for the movement and visual stimuli in increasing infant activity, the small scale of this pilot study also makes it premature to exclude the audio stimulus as an effective stimulus. Since only one infant was tested with audio stimulus, the ineffectiveness of the stimulus may be accounted for by individual preference of the infant such that the audio stimulus may not have provided sufficient positive reinforcement for the infant or that the infant may have been unable to form the association between his kicking and the stimulus during the course of the test sessions.

Table 32. Summary of Extinction Periods of Each Stimulus

		Audio			Movement			Visual		
% of Samples of Activity	Test 1	L	R	OA	L	R	OA	L	R	OA
	Test 2	L	R	OA	L	R	OA	L	R	OA
% of Bilateral/Unilateral	Test 1	E			E			E		
	Test 2	E			E			E		
Maximum Duration	Test 1	L	R	OA	L	R	OA	L	R	OA
	Test 2	L	R	OA	L	R	OA	L	R	OA
Average Duration	Test 1	L	R	OA	L	R	OA	L	R	OA
	Test 2	L	R	OA	L	R	OA	L	R	OA

Lastly, we summarize the results extracted from analyzing the extinction period. The purpose of the extinction period in the protocol was to determine if there was any carryover effect between infant learning the association between their motion and the stimulus activation when the stimulus was removed. This would provide some evidence that the association formed between the stimulus and infant activity has a long term retention. As seen from Table 32, the movement stimulus only showed an increase of 1.5 times the baseline for the average duration of the overall activity. Similarly, the audio stimulus only showed a 1.5 times increase in maximum duration of continuous activity for test 2 only. The visual stimulus showed an increase in activity with respect to the baseline for test 2 of the percentage of kicking activity for the left leg and overall activity in test 2 for maximum duration of continuous activity. However, all three stimuli show an increase in the extinction period of test two. Therefore, the effect of the acquisition period could not be determined to validate a long term retention hypothesis. Therefore, based on the results of this study alone it appears that the presence of the stimulus to provide positive feedback is essential in encouraging infant activity.

CHAPTER 8. LIMITATIONS AND FUTURE WORK

The results from this research were derived from the data of three infants with each stimulus tested with only one infant. Therefore, one of the biggest limitations of this study was the small test group; thus statistical significance for the results cannot be claimed. Another limitation for the design was due to the manual input required to close the loop and provide positive reinforcements to the infants based on their kicking activity. This meant that there was some time shift between infant motion and the activation of the stimulus. The kinematic analysis of the infant's movement was also limited due to the set of variables that could be studied from the truth data through the research by Fry et al. [28]. Kinematic variables such as the amplitude of kicking, acceleration of leg during kicking can also be crucial in identifying healthy infant kicking from atypical infant kicking behaviour as described in [30] and [35-36].

Therefore, future research effort should focus on completely automating the crib mobile by utilizing the live sensor data from the infant suit by Fry et al. in [28] and pairing it with the android app to trigger the stimuli in response to infant movement. The same sensor data can also be used to study the kinematic variables of kicking amplitude and acceleration. Research direction should also focus on determining if the kicking kinematics can be used to determine the infant's dominant leg which can be useful in explaining the infant's kicking behaviour. The experimental protocol can be modified to determine if the modification of the positive reinforcement criteria to bilateral kicking can be used to determine if infant kicking behaviour can be modified based on the design of the reinforcement protocol. Furthermore, different combinations of these stimuli may be tested to see if there is a difference in kicking activity induced by introducing the stimuli collectively then individually. Lastly, there is a need to increase the pool of infants tested to reach statistical significance for the effectiveness of movement and visual stimuli and ineffectiveness of the audio stimulus.

REFERENCES

[1] C. Morgan, I. Nonak, R.C. Dale, and N. Badawi, “Optimising motor learning in infants at high risk of cerebral palsy: a pilot study,” BMC Pediatrics, vol. 15 no.1, 2015, doi:10.1186/s12887-015-0347-2.

[2] J. Bradshaw, A.M. Steiner, G. Gengoux, and L.K. Koegel, “Feasibility and effectiveness of very early intervention for infants at-risk for autism spectrum disorder: a systematic review, ” Journal of Autism and Developmental Disorders, vol. 45 no. 3, pp. 778-794, 2014, doi:10.1186/s12887-015-0347-2.

[3] G. Csibra, “Teleological and referential understanding of action in infancy,” Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, vol 358, no. 1431, pp. 447-458., 2003, doi:10.1098/rstb.2002.1235.

[4] A.N. Meltzoff, “Understanding the intentions of others: re-enactment of intended acts by 18-month-old children.” Developmental Psychology, vol. 31 no.5, pp. 838-850., 1995, doi:10.1037/0012-1649.31.5.838.

[5] A.N. Meltzoff, and J. Decety, “What imitation tells us about social cognition: a rapprochement between developmental psychology and cognitive neuroscience,” Philosophical Transactions of the Royal Society of London. Series B: Biological, vol 358, no.1431 pp. 491-500, 2003, doi:10.1098/rstb.2002.1261.

[6] V. Goyal, W. Torres, R. Rai, F. Shofer, D. Bogen, P. Bryant, L. Prosser and M. J. Johnson, “Quantifying infant physical interactions using sensorized toys in a natural play environment,” 2017 International Conference on Rehabilitation Robotics (ICORR), 2017, doi:10.1109/icorr.2017.8009360.

[7] M. Bosanquet, L. Copeland, R. Ware and R. Boyd, “A systematic review of tests to predict cerebral palsy in young children,” Developmental Medicine & Child Neurology, vol. 55, no.5, pp. 418-426, 2013, doi:10.1111/dmcn.12140.

[8] K.V.N. Braun, N. Doernberg, L. Schieve, D. Christensen, A. Goodman and M. Y. Allsopp, “Birth prevalence of cerebral palsy: a population-based study”, Pediatrics, vol. 137, no.1, 2015, doi:10.1542/peds.2015-2872.

[9] S. S. Shivakumar, H. Loeb, D. K. Bogen, F. Shofer, P. Bryant, L. Prosser and Michelle Johnson, “Stereo 3D tracking of infants in natural play conditions,” 2017 International Conference on Rehabilitation Robotics (ICORR), 2017, doi:10.1109/icorr.2017.8009353

[10] M. M. Serrano, Y.P. Chen, A. Howard and P. A. Vela, “Lower limb pose estimation for monitoring the kicking patterns of infants,” 2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2016, doi:10.1109/embc.2016.7591156.

[11] C. Morgan, I. Novak, N. Badawi, “Enriched environments and motor outcomes in cerebral palsy: systematic review and meta-analysis,” Pediatrics, vol 132, no.3, 2013, doi:10.1542/peds.2012-3985.

[12] D. Bryant, J. Boyd, J. Harris, M. Smith, S.G. Vergara, Y.P. Chen and A. Howard, “An infant smart-mobile system to encourage kicking movements in infants at-risk of cerebral palsy,” 2017 IEEE Workshop on Advanced Robotics and Its Social Impacts (ARSO), 2017, doi:10.1109/arso.2017.8025187.

[13] E. Rogers, P. Polygerinos, C. Walsh, E.Goldfield, “Smart and connected actuated mobile and sensing suit to encourage motion in developmentally delayed infants,” Journal of Medical Devices, vol. 9, no. 3, 2015, p.030914, doi:10.1115/1.4030550.

[14] B. Sargent, H. Reimann, M. Kubo and L. Fetters, “Quantifying learning in young infants: tracking leg actions during a discovery-learning task,” Journal of Visualized Experiments, no. 100, 2015, doi:10.3791/52841.

[15] J. Heathcock, A.N. Bhat, M.A. Lobo and J.C. Galloway, “The performance of infants born preterm and full-term in the mobile paradigm: learning and memory,” Physical Therapy, 2004, doi:10.1093/ptj/84.9.808.

[16] D.W. Haley, J. Weinberg and R.R. Grunau, “Cortisol, contingency learning, and memory in preterm and full-term infants,” Psychoneuroendocrinology, vol. 31, no. 1, pp. 108–117, 2006, doi:10.1016/j.psyneuen.2005.06.007.

[17] Y.P. Chen, L. Fetters, K.G. Holt, E. Saltzman, “Making the mobile move: constraining task and environment,” Infant Behavior and Development, vol.25, no.2, pp. 195-220., 2002, doi:10.1016/s0163-6383(02)00121-2.

[18] G. Passetti, F. Cecchi, I. Baldoli, G. Sgandurra, E. Beani, G. Cioni, C. Laschi and P.Dario, "Sensorized toys for measuring manipulation capabilities of infants at home," 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2015, doi:10.1109/embc.2015.7320099.

[19] M. Zentner and T. Eerola, "Rhythmic engagement with music in infancy," Proceedings of the National Academy of Sciences, vol. 107, no. 13, pp. 5768–5773., 2010, doi:10.1073/pnas.1000121107.

[20] J. Loewy, K. Stewart, A.M. Dassler, A. Telsey and P. Homel, "The effect of music therapy on vital signs, feeding and sleep in premature infants," Pediatrics, vol.131, no.5, 2013, doi:10.1542/peds.2012-1367d.

[21] D.D. Walworth, "Effects of developmental music groups for parents and premature or typical infants under two years on parental responsiveness and infant social development," Journal of Music Therapy, vol. 46, no. 1, pp. 32–52., 2009, doi:10.1093/jmt/46.1.32.

[22] Transformania Toys, https://www.walmart.com/ip/Kids-Baby-3-in-1-Musical-Crib-Spinning-Electronic-Clover-Baby-Newborn-Mobile-Toy-for-Children-Boys-Girls/357112574.

[23] Gatt-Server, https://git.kernel.org/pub/scm/bluetooth/bluez.git/tree/test/example-gatt-server.

[24] "Mobile operating system market share worldwide." StatCounter Global Stats, gs.statcounter.com/os-market-share/mobile/worldwide.

[25] "Small 3V DC toy motor for Arduino/Raspberry-Pi/Robotics." Robomart.com, www.robomart.com/3v-dc-toy-motor.

[26] E. Ricci, A. Craig, C. Einspieler and M. Leopold, Implementation of the Prechtl General Movements Assessment of Infants in the US- Early Identification of Cerebral Palsy: A Pilot Project . www.aacpdm.org/UserFiles/file/DP25-Ricci.pdf.

[27] Adafruit Industries. "Adafruit LED Sequins - Multicolor Pack of 5." Adafruit Industries Blog RSS, www.adafruit.com/product/3377.

[28] K. E. Fry, Y. Chen and A. Howard, "Detection of infant motor activity during spontaneous kicking movements for term and preterm infants using inertial sensors." 2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2018, doi:10.1109/embc.2018.8513578.

[29] “Facts about developmental disabilities | CDC.” Centers for Disease Control and Prevention, Centers for Disease Control and Prevention, www.cdc.gov/ncbddd/developmentaldisabilities/facts.html.

[30] I. A. Trujillo Priego and B. A. Smith, “Kinematic characteristics of infant leg movements produced across a full Day.” Journal of Rehabilitation and Assistive Technologies Engineering, vol. 4, 2017, p. 205566831771746., doi:10.1177/2055668317717461.

[31] D.Gravem, M. Singh, C. Chen, J. Rich, J. Vaughan, K. Goldberg, F. Waffarn, P. Chou, D. Cooper, D. Reinkensmeyer and D.Patterson, “Assessment of infant movement with a compact wireless accelerometer system.” Journal of Medical Devices, vol. 6, no. 2, 2012, p. 021013., doi:10.1115/1.4006129.

[32] M. Fan, D. Gravam, D. M. Cooper and D. J. Patterson, “Augmenting gesture recognition with Erlang-Cox Models to identify neurological disorders in premature babies.” Proceedings of the 2012 ACM Conference on Ubiquitous Computing - UbiComp '12, 2012, doi:10.1145/2370216.2370278.

[33] C. B. Heriza, “Comparison of leg movements in preterm infants at term with healthy full-term infants.” Physical Therapy, vol. 68, no. 11, 1988, pp. 1687–1693., doi:10.1093/ptj/68.11.1687.

[34] J. C. van der Heide, P. B. Paolicelli, A. Boldrini and G. Cioni, “Kinematic and qualitative analysis of lower-extremity movements in preterm infants with brain lesions.” Physical Therapy, 1999, doi:10.1093/ptj/79.6.546.

[35] S-F. Jeng, L-C. Chen, and K-I. T. Sou “Kinematic analysis of kicking movements in preterm infants with very low birth weight and full-term infants.” Physical Therapy, vol. 82, no. 2, 2002, pp. 148–159., doi:10.1093/ptj/82.2.148.

[36] S-F. Jeng, L-C. Chen, K-I. T. Sou, W. J. Chen and H-J. Luo, “Relationship between spontaneous kicking and age of walking attainment in preterm infants with very low birth weight and full-term infants.” Physical Therapy, 2004, doi:10.1093/ptj/84.2.159.